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Organisations

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Research outputs:

Industry 4.0 – A challenge for variation simulation tools for mechanical assemblies

Variation Analysis (VA) is used to simulate final product variation, taking into consideration part manufacturing and assembly variations. In VA, all the manufacturing and assembly processes are defined at the product design stage. Process Capability Data Bases (PCDB) provide information about measured variation from previous products and processes and allow the designer to apply this to the new product. A new challenge to this traditional approach is posed by the Industry 4.0 (I4.0) revolution, where Smart Manufacturing (SM) is applied. The manufacturing intelligence and adaptability characteristics of SM make present PCDBs obsolete. Current tolerance analysis methods, which are made for discrete assembly products, are also challenged. This paper discusses the differences expected in future factories relevant to VA, and the approaches required to meet this challenge. Current processes are mapped using I4.0 philosophy and gaps are analysed for potential approaches for tolerance analysis tools. Matching points of simulation capability and I4.0 intents are identified as opportunities. Applying conditional variations, incorporating levels of adjustability, and the unsuitability of present Monte Carlo simulation due to changed mass production characteristics, are considered as major challenges. Opportunities including predicting residual stresses in the final product and linking them to product deterioration, calculating non-dimensional performances and extending simulations for process manufactured products, such as drugs, food products etc. are additional winning aspects for next generation VA tools.

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Application of a graphical scheme for representing the mode of action of products for identification of key characteristics

In order to identify where to focus the tolerance analysis during the product development process, it is beneficial to find the key characteristics. However, for highly integrated, multiple-state products, product designers have difficulties in efficiently communicating and tracking the complex mode of action. As a consequence, not all relevant key characteristics are found in the initial screenings. We propose a systematic graphical representation scheme for modelling the mode of action of products, and we apply this scheme on a case example, in order to illustrate its applicability and its usefulness for the identification of key characteristics.
Product Robustness Philosophy - A Strategy Towards Zero Variation Manufacturing (ZVM)
A product is referred to as robust when its performance is consistent. In current product robustness paradigms, robustness is the responsibility of engineering design. Drawings and 3D models should be released to manufacturing after applying all the possible robust design principles. But there are no methods referred for manufacturing to carry and improve product robustness after the design freeze. This paper proposes a process of inducing product robustness at all stages of product development from design release to the start of mass production. A manufacturing strategy of absorbing all obvious variations and an approach of turning variations to cancel one another are defined. Verified the application feasibility and established the robustness quantification method at each stage. Theoretical and actual sensitivity of different parameters is identified as indicators. Theoretical and actual performance variation and accuracy of estimation are established as robustness metric. Manufacturing plan alignment to design, complimenting the design and process sensitivities, countering process mean shifts with tool deviations, higher adjustable assembly tools are enablers to achieve product robustness.
The Applicability of CAT tools in industry – boundaries and challenges in tolerance engineering practice observed in a medical device company

While the capabilities of computer-aided tolerancing (CAT) tools are increasing continuously, their compatibility with design processes in industry is not necessarily a given. This paper seeks to examine potential method barriers and challenges that limit the applicability and general uptake of CAT software in industry, through interviews with practitioners ranging from tolerance engineering specialists to project managers. The study identifies several issues met by practitioners that limits or prevents their use of CAT software, pointing to several unmet needs.

The importance of robust design methodology

While a systematic quality strategy is of crucial importance for the success of manufacturing companies, the universal applicability and effectiveness of implemented quality management practices were called into question by a number of
major product recalls in recent years. This article seeks to illustrate how already simple analyses and early stage design methods can help to better understand one of the potential reasons for these failures, namely the variation inherent in manufacturing, assembly, and use processes. Usually thoroughly controlled in production, it seems as if particularly the risk of unanticipated variation effects remain largely underestimated and thus unaccounted for in design practice, sometimes with disastrous consequences. To foster the awareness of this variation and to illustrate the benefits of its early consideration in product development, this paper reviews one of the most infamous recalls in automotive history, that of the GM ignition switch, from the perspective of Robust Design. It is investigated if available Robust Design methods such as sensitivity analysis, tolerance stack-ups, design clarity, etc. would have been suitable to account for the performance variation, which has led to a number of fatal product defects and the recall of 30 million vehicles. Furthermore, the disclosed legal case files were examined, offering a unique opportunity to examine how technical malfunctioning of the ignition switch could stay undetected long enough to result in fatalities.

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- Web of Science (2012): Indexed yes
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Generally, there is little disagreement that an early consideration of dimensional accuracies achieved in production is conducive to the success of development of injection molding products. While different process capability databases (PCDBs) provide guidance for a meaningful estimation of the expected part variation, the adoption of corresponding guidelines and (proprietary) software tools seems to be, however, limited in industrial practice so far. This research paper addresses the gap between the available PCDBs and the requirement of designers in practice and investigates the key drivers for an improved applicability of corresponding database solutions in an industrial context. A survey of database users at all phases of product value chain in the plastic industry revealed that 59% of the participating companies use their own, internally created databases, although reported to be not fully adequate in most cases. Essential influences are the suitability of the provided data, defined by the content such as material, tolerance types, etc. covered, as well as its accuracy, largely influenced by the updating frequency. Forming a consortium with stakeholders, linking database update to technology changes and connecting dimensioning standards to database offerings are proposed solutions.
Exact Constraint Design and its potential for Robust Embodiment

The design of exact, also referred to as minimal, constraints means applying just enough constraints between the various components of a mechanical assembly, in order to unambiguously define their positions in six degrees of freedom (3 translations, 3 rotations), their desired motions respectively. To ensure a predictable and reliable product performance, a systematic design of the corresponding elementary mechanical interfaces between components is of utmost importance. Over constraints, i.e., part-to-part connections with redundant interfaces which constrain one single degree of freedom, are largely susceptible to variation and therefore result in design solutions which frequently experience production/assembly issues, reduced performance, excessive and non-predictable wear-rates, etc.

Being a basic rule of embodiment design, literature provides various well-known and widely applied approaches for Exact Constraint Design. Examples are the calculation of a mechanisms’ mobility using the Grubler-Kutzbach criterion, the analysis of statically determinate assemblies by means of the screw theory or so-called Schlussartenmatrizen, as well as the analysis of engaging surfaces in terms of location schemes or interface ambiguity. However, despite the various existing approaches, workshops with practitioners and academics have shown that the systematic design of optimal constraints appears to be cumbersome for many engineers. Based on an overview of the most relevant approaches for Exact Constraint design, this contribution therefore reviews the challenges experienced by the workshop participants, discusses the necessity of kinematically correct constraints for robustness, and derives an initial prescriptive procedure for a coherent design of constraints throughout the embodiment design phase, which, despite a variety of available approaches, seems to be still missing.

Mass Production Tools and Process Readiness for Uniform Parts—Injection Molding Application

A mass production always aims to produce uniform performing products. Production tools such as pressing dies, casting dies and injection moulds, play a significant role by producing uniform parts for achieving final products. Tool complexity increases when multiple cavities are present. These tools pass through several stages of quality maturation, before starting production, where the tool capability for part uniformity can be assessed, corrected and aligned to mass...
production variables. This research article describes the process of systematic understanding of the impact of variables and of finding opportunities to counter them. Application is assessed over a hypothetical plastic injection mould and found feasible. Proposed process could evaluate the tool capability for producing uniform parts, at its digital design verification and its physical validation.

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Quantifying the robustness of process manufacturing concept – A medical product case study
Product robustness refers to the consistency of performance of all of the units produced. It is often the case that process manufactured products are not designed concurrently, so by the end of the product design phase the Process Manufacturing Concept (PMC) has yet to be decided. Allocating process capable tolerances to the product during the design phase is therefore not possible. The robustness of the concept (how capable it is to achieve the product specification), only becomes clear at this late stage and thus after testing and iteration. In this article, a method for calculating the unit-to-unit robustness of an early-stage for a PMC is proposed. The method uses variability and adjustability information from the manufacturing concept in combination with sensitivity information from products' design to predict its functional performance variation. A Technology maturation factor for addressing varied process capability confidence was applied. A four-step process of Define, Connect, Map and Quantify was proposed for calculating PMC robustness and was tested for a wound-care product. The results show that the method was applicable and enabled PMC selection based on quantified robustness. The case also demonstrates that higher robustness is possible even at higher parameter variability with suitable measurements and adjustability.

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The variation management framework (VMF): A unifying graphical representation of robust design

In this article a framework for robust design and variation management is proposed by combining central models to Robust Design, namely, the Quality Loss Function, the Transfer Function, and the Domains of Axiomatic Design. The Variation Management Framework (VMF) shows how variation can be mapped from production variation right through to the quality loss perceived by the customer for a single characteristic chain. Seven levers which can be activated to increase product quality are described and positioned on the VMF and variation metrics are proposed.

General information
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Contributors: Howard, T. J., Eifler, T., Pedersen, S. N., Göhler, S. M., Boorla, S. M., Christensen, M. E.
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Robustness Metrics: Consolodiating the multiple approaches to quantity Robustness

The robustness of a design has a major influence on how much the product's performance will vary and is of great concern to design, quality and production engineers. While variability is always central to the definition of robustness, the concept does contain ambiguity and although subtle, this ambiguity can have significant influence on the strategies used to combat variability, the way it is quantified and ultimately, the quality of the final design. In this contribution the literature for robustness metrics was systematically reviewed. From the 108 relevant publications found, 38 metrics were determined to be conceptually different from one another. The metrics were classified by their meaning and interpretation based on the types of information necessary to calculate the metrics. Four different classes were identified: 1) Sensitivity robustness metrics; 2) Size of feasible design space robustness metrics; 3) Functional expectancy and dispersion robustness metrics; and 4) Probability of conformance robustness metrics. The goal was to give a comprehensive overview of robustness metrics and guidance to scholars and practitioners to understand the different types of robustness metrics and to remove the ambiguities of the term robustness. By applying an exemplar metric from each class to a case study, the differences between the classes were further highlighted. These classes form the basis for the definition of four specific sub-definitions of robustness, namely the ‘robust concept’, ‘robust design’, ‘robust function’ and ‘robust product’.

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Toward Meaningful Manufacturing Variation Data in Design - Feature Based Description of Variation in Manufacturing Processes

The need to mitigate the effects of manufacturing variation already in design is nowadays commonly acknowledged and has led to a wide use of predictive modeling techniques, tolerancing approaches, etc. in industry. The trustworthiness of corresponding variation analyses is, however, not ensured by the availability of sophisticated methods and tools alone, but does evidently also depend on the accuracy of the input information used. As existing approaches for the description of manufacturing variation focus however, almost exclusively, on monitoring and controlling production processes, there is frequently a lack of objective variation data in design. As a result, variation analyses and tolerancing activities rely on numerous assumptions made to fill the gaps of missing or incomplete data. To overcome this hidden subjectivity, a schema for a consistent and standardised description of manufacturing variation is suggested. It extends existing ISO GPS annotation by information about influences on the manufacturability of a chosen design solution and in this way enables the systematic acquisition of variation data meaningful for design practice.

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Robust Reliability or reliable robustness? - Integrated consideration of robustness and reliability aspects

Commonly, the terms reliability and robustness are used to describe products and processes, which are in accordance with the customer requirements and fulfill 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.

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Design to Process Capabilities: challenges for the use of Process Capability Databases (PCDBs) in development

In approaches such as Robust Design, Tolerance Management, Design for Six Sigma (DfSS), etc. there is little disagreement that a better understanding of inevitable production variation is conducive to the success of development projects [Eifler et al. (2013), Arvidsson and Gremyr (2008), Karmakar and Maiti (2012), Breyfogle (2003)]. At the same time, information on the achievable manufacturing accuracy or the supplier's performance is usually inaccurate and largely qualitative in early development stages. Design decisions as well as the choice of manufacturing processes, therefore, often rely on experiential approaches or expert judgment. There are numerous examples that this subjective assessment of potential variation and a mostly informal communication between design and production engineers can result in non-satisfying product or manufacturing solutions. Whereas overestimated production capabilities may lead to low yields and a cost/time overrun, conservatively underestimated capabilities affect quality through the reduced design space, or through increased play, rattle/noise, size or weight. A possibility to overcome the subjective assessment of variation in development projects is a Process Capability Data Base (PCDB) offering valuable insight into the actual or expected performance of production processes (Tata and Thornton, 1999). But although the potential benefits as well as initial challenges for the use of PCDBs have been addressed in earlier research, e.g. by Delaney and Phelan (2008), Kern (2003) or Tata and Thornton (1999), a widespread adoption in industry cannot be observed. As already stated by Okholm et al. (2014), there are many open questions and a methodical support how to generate, provide and use generalized production variation data still seems to be missing. To foster the use of corresponding databases and to stimulate further research, this paper gives an overview about the scope of potential applications for a PCDB in product development. Furthermore, the expected manufacturing accuracy of specific product characteristics/features is discussed. For the generalization of measurement data, a DOE (Design of Experiments)-based approach is proposed to identify influencing factors related to the production accuracy of each geometric feature, using the example of metal shear forming processes.

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Improving process capability database usage for robust design engineering by generalising measurement data

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Proceedings of the First International Symposium on Robust Design 2014
The symposium concerns the topic of robust design from a practical and industry orientated perspective. During the 2 day symposium we will share our understanding of the need of industry with respect to the control of variance, reliability issues and approaches to robust design. The target audience for the symposium therefore will aim to attract equal numbers of industry and academic delegates with two separate paper submission tracks.

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Robustness and Reliability of the GM Ignition Switch - A forensic Engineering case
This paper uses forensic engineering from the perspectives of Robust Design and Reliability Engineering to review one of the most infamous recalls in automotive history, that of the GM ignition switch. The design, engineering and management failures in this case ultimately resulted in a fine of $35 million, the recall of 2.6 million vehicles and the death of at least 13 people. In a systematic approach, design clarity, tolerance stack-ups, sensitivity analysis, etc. are used to analyse the ignition switch itself and to extend the usual consideration of reliability issues to the impact of variation on the design. In addition to this quantitative analysis, the legal case files have been examined revealing multiple misjudgments and errors throughout the product development process. The analysis revealed a lack of overview regarding to interrelated functionality, a lack of respect for the requirement specification and clarity in the specification itself, and finally a culture of silence rather than confrontation and remedy.

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The Variation Management Framework (VMF) for Robust Design

Robust Design is an approach to reduce the effects of variation. There are numerous tools, methods, and models associated with robust design, however, there is both a lack of a process model formalising the step of a robust design process and a framework tying the models together. In this paper we propose a framework for robust design and variation management by combining central models to Robust Design, namely, the Quality Loss Function, the Transfer Function, and the Domains of Axiomatic Design. The framework shows how variation can be mapped from production right through to quality loss in the marketplace and identifies areas where action can be taken against variation. An additional benefit of the framework is that it makes the link between visual/sensory/perceptual robustness, product robustness, and production variation (Six Sigma).

A classification of the industrial relevance of robust design methods

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Projects:

**A coherent approach to virtual assessments of structural robustness**
Nerenst, T. B., PhD Student, Department of Mechanical Engineering
Nielsen, K. L., Main Supervisor
Christensen, M. E., Supervisor
Eifler, T., Supervisor
01/02/2019 → 31/01/2022
Project: PhD

**Developing robust concepts for highly integrated products**
Sigurdarson, N. S., PhD Student, Department of Mechanical Engineering
Howard, T. J., Main Supervisor
Christensen, M. E., Supervisor
Eifler, T., Supervisor
Industrial PhD
01/03/2018 → 28/02/2021
Award relations: Developing robust concepts for highly integrated products
Project: PhD

**Early application of tolerance design**
Bjarklev, K., PhD Student, Department of Mechanical Engineering
Mortensen, N. H., Main Supervisor
Eifler, T., Supervisor
Krause, D., Examiner
Hildre, H. P., Examiner
Kiil, H., Examiner
Samfinansierede - Virksomhed
15/12/2015 → 14/12/2018
Award relations: Early application of tolerance design
Project: PhD

**Quantified Robust Design: Measurement of sensitivity, variance and impact**
Boorla, S. M., PhD Student, Department of Mechanical Engineering
Howard, T. J., Main Supervisor
Eifler, T., Supervisor
De Chiffre, L., Examiner
Thornton, A., Examiner
Söderberg, R., Examiner
Samfinansierede - Virksomhed
15/01/2015 → 07/05/2018
Award relations: Quantified Robust Design: Measurement of sensitivity, variance and impact
Project: PhD

**Metric-driven Robust Design \& Robustness Quantification of Complex Engineering Systems**
Göhler, S. M., PhD Student, Department of Mechanical Engineering
Howard, T. J., Main Supervisor
Eifler, T., Supervisor
McMahon, C. A., Examiner
Dantan, J., Examiner
Söderberg, R., Examiner
Samfinansierede - Virksomhed
15/01/2014 → 29/05/2017
Award relations: Metric-driven Robust Design \& Robustness Quantification of Complex Engineering Systems
Project: PhD

**Quantifying Functional Requirements as Robust Design Target Values**
Pedersen, S. N., PhD Student, Department of Mechanical Engineering
RDP: DTU-Novodisk Robust Design Programme
This project is a research and educational programme focusing on the development and application of Robust Design, Tools, Methods and Processes. Robust Design is essential to a country's competitiveness in production. When a design is robust it means that it is insensitive to small variations in production and therefore over large production volumes over long lifetime, will continually give a consistent performance to the customer.

Howard, T. J., Project Manager, Department of Mechanical Engineering
Pedersen, S. N., PhD Student, Department of Mechanical Engineering
Christensen, M. E., PhD Student, Department of Mechanical Engineering
Göhler, S. M., PhD Student, Department of Mechanical Engineering
Eifler, T., Supervisor, Department of Mechanical Engineering
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Collaborators: Novo Nordisk AS
Project: Research