DTU

Applying Robust Design in an Industrial Context

PhD Thesis

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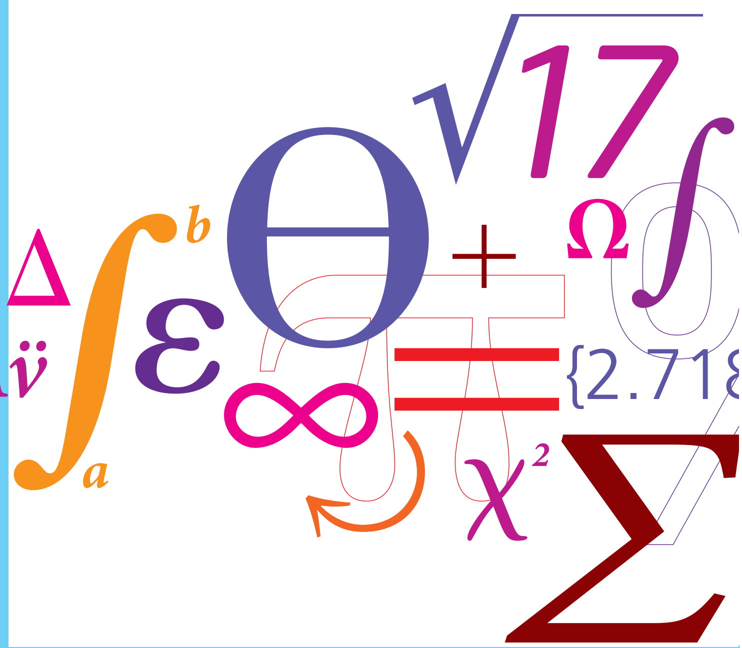

Martin Ebro Christensen
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PhD Thesis
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Abstract

The ability to develop and manufacture products of high quality is a decisive competitive parameter for any production company. The costs of *non-quality,* i.e. not fulfilling the functional requirements for a given product, are considerable, often manifesting as scrapped products, product recalls, lost sales, customer complaints and delayed product launches. Over time, the responsibility for obtaining consistent product performance has moved upstream in the development process, motivated by the saved costs of discovering and removing design errors prior to large investments in manufacturing tools and production facilities. An extensive set of frameworks, tools and methods are available for ensuring and improving product quality.

The research presented in this thesis focuses on the Robust Design Methodology – which is a collection of methods and tools intended to support the design engineer in creating products with consistent performance, despite influences from manufacturing variability and use conditions. Although Robust Design is claimed to be applicable during the early phases of product development, surveys have shown (Thornton et al 2000; Gremyr et al 2003; Araujo et al 1996) that it is only used by a small minority of production companies and it has been criticised for being too complex to use and only being applicable during late-stage design optimisations. This project addresses these issues and contributes to the industrial understanding and application of Robust Design methods and principles, by attempting to remove the existing barriers for widespread industrial use of the Robust Design Methodology.
The research finds, through the defintion of an impact model linking non-robustness to profit loss in an organisation. The link is made through a series of causal factors such as overly tight tolerances, high scrap rates, missed launch dates, and product recalls. All of these causal factors are considered as symptoms of non-robustness and are used in an applicability assessment to gauge the potential benefit of implementing Robust Design in an organisation.

One particular symptom has been investigated in greater detail to partially verify the impact model, namely the 'Misapplication of R&D resources'. In one case-company it is shown that R&D resources used to make late design changes after 'Design Verification', where the design is ideally frozen and prepared for production, was up to 400% more than used during the design and development phase! On deeper investigation of the change notes, it is shown that over 60% of these are related to kinematic and mechanical interface issues.

With such apparent robustness issues embedded into the geometry of designs seen throughout industry, Robust Optimisation, which is the main focus in academia, is quite futile. There is a need to lay out the foundation for the Robust Design Methodology (RDM) using the approaches of kinematic design and design clarity, two fundamental methods to be added to RDM providing the guidance for designing robust mechanical architectures. Furthermore a set of 15 robust design principles for reducing the variation in functional performance is compiled in a format directly supporting the work of the design engineer.

With these foundational methods in place, the existing tools, methods and KPIs of Robust Design are reviewed and positioned within a framework, which also identifies the need for quantitative, leading indicators of robustness, which are now further developed in the so-called Six Theta® framework. However, the lack of adoption of robust design is not simply due to the lack of simplici-

ty, education and coherence around the available tools and methods, but also the organisational change management that is key to any successful implementation.

After identifying four companies seen as front runners in terms of robust design implementation, all from different industries but based on mechanical design, a series of interviews were conducted to identify best practice procedures. The analysis and results showed that there is no single solution and each company had a different approach, which worked for their company culture and the nature of the products they were developing. As a result different implementation archetypes are created so that R&D managers are able to choose and take inspiration for the archetype that they think best fits their company.

The methods Kinematic Design and Design Clarity are applied in a case project in a consumer electronics company to give an indication of the effects. The data suggests that there is a potential for a substantial reduction of late-stage design changes in comparison to the original benchmark studies prior to the methods being implemented.

Resumé (in Danish)

Evnen til at udvikle og fremstille produkter af høj kvalitet er en afgørende konkurrenceparameter for produktionsvirksomheder. Omkostningerne ved såkaldt *non-quality*, dvs. manglende opfyldelse af de funktionelle krav til produktet er betydelige, og dækker bl.a. over kasserede produkter, tilbagekaldelser, kundeklager og forsinkede produktlanceringer. Der har været en tendens mod at placere ansvaret for produktkvaliteten i udviklingsfasen, hvilket har været drevet af et ønske om at finde og fjerne fejlene i produktet, inden der investeres i dyre fremstillings- og montageværktøjer. Der eksisterer et omfattende metodesæt rettet mod at sikre og forbedre produktkvaliteten generelt. Forskningen, der præsenteres i denne afhandling, omhandler Robust Design Metodesættet, som er en samling af metoder og værktøjer, hvis formål er et støtte udviklingsteamet i at designe produkter, med en ensartet *performance*, på trods af de variationer der kommer fra fremstillingen og brugen af produktet. Selv om Robust Design i litteraturen bliver beskrevet som værende anvendeligt i de tidlige udviklingsfaser, har undersøgelser vist (Thornton et al 2000; Gremyr et al 2003; Araujo et al 1996) at kun få virksomheder kender og bruger Robust Design, primært fordi det er for komplekst og fordi det betragtes som et optimeringsværktøj til brug i de sene udviklingsfaser. Som en følge af dette, bliver potentialet for at designe produkter af høj kvalitet ikke udnyttet og virksomhederne oplever unødvendige problemer med lange *ramp-up* tider, forsinkede produktlanceringer og intensiv *rework* og redesign af produkterne kort før lanceringen. Dette projekt adresserer disse problemer og bidrager til den industrielle forståelse og anvendelse af Robust Design Metodesættet, ved at forsøge at fjerne de barrierer der eksisterer for en generel anvendelse af Robust Design.

Projektet har udviklet en *impact-model* der viser sammenhængen mellem mangel på robusthed og tab af profit for virksomheden. Sammenhængen er fundet gennem serier af kausale faktorer som fx stramme produktionstolerancer, høje kassationsrater, udskudte produktlanceringer og produkttilbagekaldelser. Alle disse faktorer er symptomer på manglende robusthed og kan derfor anvendes i en vurdering af de potentielle effekter ved at implementere Robust Design i en organisation.

Èn af disse faktorer er blevet analyseret yderligere, for dermed delvist at kunne verificere impactmodellen, nemlig 'Ikke-optimal brug af R&D ressourcer'. I en case virksomhed blev det vist, at andelen af R&D-ressourcer der anvendes til at lave sene designændringer, dvs. efter designverifikationen, hvor konstruktionen ideelt set er *låst*, var op til 400% højere end den andel der blev brugt i den egentlige udviklingsfase! Gennem en yderligere analyse af virksomhedens ændringsanmodninger (*change requests)* blev det vist, at over 60% af de designændringer der blev foretaget relaterede sig til kinematik og problemer med de mekaniske interfaces.

De fundamentale udfordringer, der ligger indlejret i selve geometrien af konstruktionerne gjorde det tydeligt, at de optimeringer der generelt er det primære fokus i den eksisterende litteratur og forskning, ikke er tilstrækkelige. Der var et behov for at definere de fundamentale retningslinjer for Robust Design Metodesættet (RDM), baseret på kinematisk design og entydighed, hvilket er blevet gjort som en del af dette arbejde. Derudover præsenteres en samling af 15 robust design principper, som kan anvendes direkte i udviklingsarbejdet som støtte for konstruktøren. Med disse fundamentale metoder på plads, blev de eksisterende metoder, værktøjer og KPI'er inden for Robust Design gennemgået og positioneret i et rammeværk, som samtidig også viser at der er et behov for metoder med ledende, kvantitative indikatorer på robusthed.

Den manglende anvendelse af Robust Design i industrien er dog ikke kun et spørgsmål om at simplificere og skabe forståelse for de metoder og værktøjer der er til rådighed inden for Robust Design. Den relaterer sig også til den nødvendige forandringsledelse af udviklingsafdelingen der skal til for at opnå en succesfuld implementering. Fire virksomheder, der alle anses som frontløbere inden for Robust Design er blevet identificeret. De dækker over forskellige segmenter og lande, men har til fælles, at de alle udvikler og producerer mekaniske produkter. Der er foretaget interviews i virksomhederne for at afdække deres *best-practice.* Analysen og resultaterne viser, at der ikke findes en éntydig måde at implementere og anvende Robust Design på. Hver virksomhed har sin egen tilgang, der er tilpasset til deres kultur og den kontekst de opererer i. Som et resultat heraf, præsenteres fire arketyper for implementering og anvendelse af Robust Design, målrettet mod R&D-managers, som kan finde inspiration til at finde en implementering, der passer deres virksomhed.

De udviklede metoder er blevet anvendt i et case-projekt i en virksomhed, der udvikler forbrugerelektronik for at give en indikation af effekterne. De indhentede data viser, at der er et betydeligt potentiale for at reducere spild og antallet af designændringer i de sene udviklingsfaser.

Preface

This thesis summarises the research carried out during the industrial PhD-project “Applying Robust Design in an Industrial Context”. The project has been carried out in collaboration with the Danish consulting company Valcon Design A/S and the Technical University of Denmark (DTU) over a course of three and a half years, from 2012 to 2015.

The thesis represents a milestone on a journey that started in 2004, where I worked as a product development consultant together with Janus Juul Rasmussen. During our frequent trips to Jutland, we had long discussions about why the products we were designing seemed to suffer less from quality issues and ramp-up problems compared to the typical experiences of our clients. Over the years, our interest in the philosophical and theoretical aspects of product complexity led us into the fields of axiomatic design, reliability engineering, variation management and robust design and over time we developed a language and methodology that we used in our daily work, which in many ways resembled the methods and theories of Robust Design (RD). Although the underlining thoughts of designing products insensitive to variation were identical to Robust Design, the underlying methods differed in nature. But how? And if Robust Design was the solution to improvements in product quality, then it seemed alarming that although we had an extensive network in Danish production companies, we had never experienced *Robust Design* being used or mentioned – it seemed to be non-existent in Danish industry!

During the same period, my professional focus gradually shifted from *designing products* to *designing product development processes.* After having led a large Robust Design Programme in the Danish pharmaceutical company Novo Nordisk, I decided to take out the time to dive even deeper into the field of Robust Design, hoping to emerge with a more well-defined and coherent process and set of methods for applying Robust Design – and even more important: identifying something that could be used in industry and help close the gap towards research. After three years of pursuing this, I am looking forward to presenting the results of the journey so far.

I have many people to thank for helping me on this journey. I would like to thank the case companies in my project, who have actively helped with data, feedback, and discussions as well as accepting to try new methods and hosting my master's project students. Thanks to Novo Nordisk, Ergolet, Radiometer and especially Bang & Olufsen. A special thanks to Jesper Olesen and Bent Larsen from Bang & Olufsen for their time and commitment. When I started as a PhD-student, I was quite alone within my research field at DTU, and as a consequence, I have been extremely happy to work together with my co-authors from universities abroad: Lars Krogstie and Tobias Eifler. Thanks for the many fruitful discussions on Skype and pleasant workshops in Germany, Sweden and at DTU.

Furthermore, I am in deep gratitude to my former business partner and current industrial supervisor, Janus Juul Rasmussen. We set sail for a long and ambitious journey in 2006, when we started Valcon Design together, and I could not imagine a better travelling companion. I truly enjoy our discussions and am proud of the results we have accomplished together. We said we would change the way Danish industry does product development and I think we are on the way. Thank you for supporting the idea of the PhD-project and for your mentoring and inspiration.

Also, I am extremely lucky to have had Thomas J. Howard as my academic supervisor. When we started the project, robust design was not an active research field at DTU and now we have developed a brand new course with 180 participants to date, we have had 20+ master project students doing projects on Robust Design, we have set up a research group with 5 full-time researchers at DTU, founded a Robust Design Special Interest Group within the Design Society and created an International Symposium on Robust Design as well as an annual Robust Design Day. The results speak for themselves and I would like to thank you for your hard work and sincere dedication to my project and to establishing Robust Design at DTU and in Danish industry.

Finally, I would like to thank my lovely wife and best friend Marianne, and our three kids, Bjørn, Anna and Silja. You mean the world to me, and I want to thank you for being who you are and for not only supporting the decision to do a PhD-project, but also for being there along the journey!

Martin Ebro Christensen
Kgs. Lyngby, August 2015

Abbreviations Used

Abbreviation	Meaning
DFA	Design for Assembly
DFM	Design for Manufacture
DRM	Design Research Methodology
ETA	Event Tree Analysis
FMEA	Failure Modes & Effects Analysis
FP	Functional Performance
FTA	Fault Tree Analysis
QFD	Quality Function Deployment
QLF	Quality Loss Function
RD	Robust Design
RDM	Robust Design Methodology
S/N-ratio	Signal to noise-ratio
SPC	Statistical Process Control
TF	Transfer Function
VMEA	Variation Mode & Effects Analysis

The foundation of the thesis

The thesis is based on the publications listed from A-E below. Additional publications have also been written during the course of the PhD. These are not appended to the thesis, but are listed below as supplementary publications for reference.

A. **A Classification of the Industrial Relevance of Robust Design Methods**
Eifler, T., Christensen, M. E., & Howard, T. J. (2013). In *19th International Conference on Engineering Design* (pp. 427-436).
B. **The Foundation for Robust Design: Enabling Robustness Through Kinematic Design and Design Clarity**
Ebro, M. E., Howard, T. J., & Rasmussen, J. J. (2012). In Design 2012-12th International Conference on Design (pp. 817-826).
C. **Robust Design Principles for Reducing Variation in Functional Performance**
Ebro, M., & Howard, T.J. (Accepted) Journal of Engineering Design
D. **How to Implement and Apply Robust Design: Insights from Industrial Practice**
Krogstie, L., Ebro, M., & Howard, T. J. (2014). Total Quality Management & Business Excellence, (ahead-of-print), 1-19.
E. **A Robust Design Applicability Model**
Ebro, M., Krogstie, L., & Howard, T.J. (2015). In *20th International Conference on Engineering Design*

Supplementary publications

F. **Mechanisms and Coherences of Robust Design Methodology: A Robust Design Process Proposal**
Göhler, S.M., Ebro, M., & Howard, T.J. (submitted) Total Quality Management & Business Excellence
G. **Robust Design Requirements Specification: A Quantitative Method for Requirements Development Using Quality Loss Functions**
Pedersen, S.N., Ebro, M., & Howard, T.J. (submitted) Journal of Engineering Design.
H. **Robust Design Impact Metrics: Measuring the effect of implementing and using Robust Design**
Ebro, M., Olesen, J., & Howard, T.J. (2014) 1st International Symposium on Robust Design, 2014
Open-source link to paper: http://orbit.dtu.dk/fedora/objects/orbit:134953/datastreams/file_ea9f7d70-f08d-463c-bdaf-499a35bc0039/content
I. **The Variation Management Framework (VMF) for Robust Design**
Howard, T. J., Ebro, M., Eifler, T., Pedersen, S., Göhler, S. M., Christiansen, A., & Rafn, A. (2014). In 1st International Symposium on Robust Design (pp. 171-175)
Open-source link to paper: http://orbit.dtu.dk/fedora/objects/orbit:134955/datastreams/file_13747761-ba04-4c70-807b-d6de0d463e74/content

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1. Introduction

In 2010, the car manufacturer Toyota, was forced to recall 2.3 million cars due to issues with the accelerator pedal, causing the pedal to stick and not return to its default position under "very rare circumstances" ("Recall Fix: Toyota Confirms Plan", 2015). The cost of the recall, including court settlements, is estimated to be $3.1 billion ("Toyota in $1.1 Billion Gas Pedal Settlement", 2015). Other stories involving product recalls occur in the press from time to time. The potential benefits of being able to prevent such quality issues from occurring are obvious and in a global market with increasing demands on productivity, cost, and time-to-market, being able to control and reduce the costs of *non-quality,* is an important competitive parameter.

1.1 Introduction to Robust Design

Prior to this research project, I worked eight years in industry as a product developer and product development consultant with the opportunity of working within a wide variety of industrial segments (automotive, medical devices, consumer electronics), covering many different types of products (from wind turbines to hearing aids) and with annual production volumes ranging from a few hundred to 500 million. Despite their differences, virtually all projects in all of the companies were struggling with the same challenges and symptoms (Figure 1): Long production ramp-up times, variation and lack of predictability in functional performance, noise and vibrations, unexplainable wear, etc. These symptoms are related to subsequent issues such as delayed milestones, customer complaints and product recalls, which in turn lead to various types of cost, such as scrap, reimbursements to customers, loss of brand value, and service repairs. The costs related to quality can be divided into four categories (Booker et al 2001):

1. **Prevention costs** – design reviews, training, analyses, simulations
2. **Appraisal Costs** – inspection, testing
3. **Failure costs** – rework, scrap, design changes, recalls, service, liability/warranty
4. **Lost opportunities** – reputation, late market entry

The combined quality costs are estimated to be between 10-40% of a company's revenue (Mahmood et al 2014) and therefore represent a significant opportunity for improving the profit of the company, if they can be reduced. It is worth noting, that some quality costs may not even be registered by the company, because they are indirect and therefore not included in the accounts. As an example, a delayed launch of a new product will reduce the time the product is available on the market and hence lost profit, but this cost cannot be found on the company accounts.

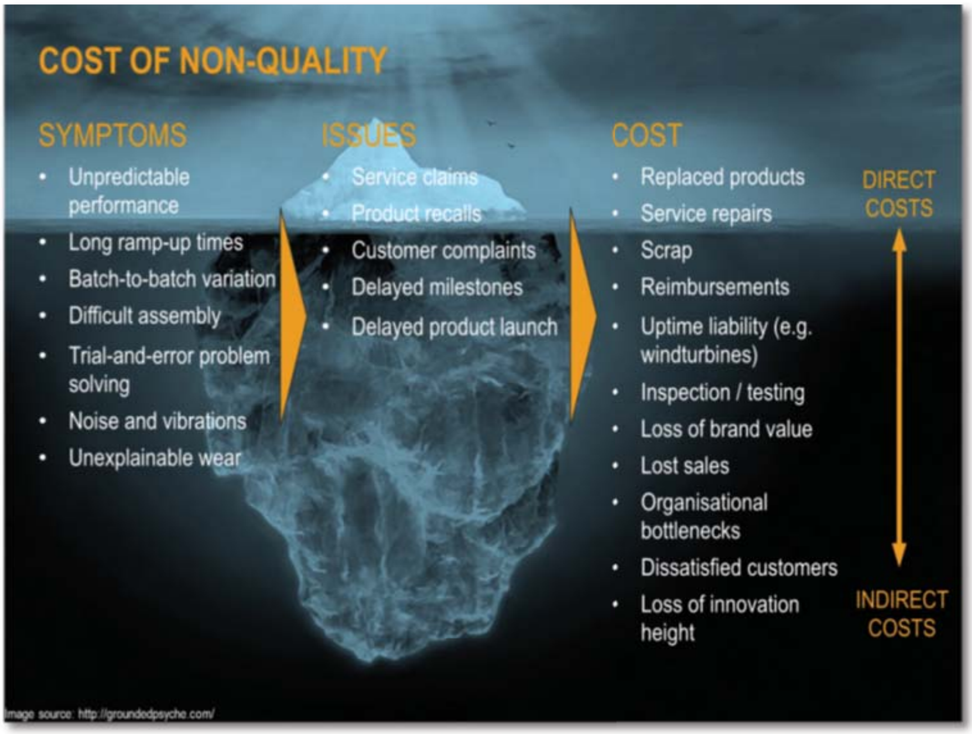


Figure 1 Symptoms, issues and costs often experienced in product development organisations.

1.2 Historical Perspective on Robust Design

Intuitively, the earlier in the development process a quality issue is discovered, the less expensive it is to correct and therefore there is a natural interest in identifying issues as early as possible. This is also reflected in the historical development of *quality engineering*, where the efforts have moved upstream in the development process during the last century. Originally, quality was obtained by inspection, i.e. controlling all of the products before they left the factory gate, and scrapping or reworking any products not fulfilling specifications. In the 1920's, the notion of improving quality by process control was introduced by Shewhart (1931) and it developed into Statistical Process Control (SPC), which is widely used in production companies today. This strategy is based on monitoring and optimising the production and assembly processes, thereby increasing the probability that the resulting product fulfils its requirements. From the 1960's and onwards, attention was directed at *embedding* quality in the product during the design phase. This change was driven by Deming (Logothetis, 1992) and Crosby (1969), who contributed to the development of Total Quality Management that focused on the managerial aspects of quality engineering and Taguchi (1986), who was the pioneer of Robust Design that focuses on obtaining product quality already during the design of the product. An overview of the historical transition is shown in Table 1. Although the activities and methods for ensuring product quality have moved upstream in the development process, inspection and process control are still widely used in industry as part of a coherent quality engineering strategy, which involves a variety of quality assurance activities.

Table 1 Methods and costs for detecting and eliminating quality issues

Phase in which a quality issue is discovered	In design	In production	In assembly	In market
Methods for identifying and preventing quality issues	Experiments/Tests Simulations Design Principles	(Statistical) Process Control	Test Inspection	N/A
Cost and methods for removing quality issues	€ Change design	€€ Adjust process parameters. Scrap/rework components	€€€ Scrap/rework complete product, module or batch	€€€€ Recall Product Service of products Replace product

It can be helpful to divide product failures into two categories, based on how often they occur (Figure 2). Failures that occur in the majority or all samples of a product can be referred to as *design failures*. An example of this could be a screw connection that is incorrectly dimensioned, so the nominal screw always breaks during normal use. These types of failures are easily identified during the prototyping phase, due to the high probability of failure, and the fact that they fail also at nominal conditions. Because these failures are found early in the development process, the cost of correcting them is relatively low. The second type of failures, *robustness failures,* only occurs under certain circumstances. An example of this could be a screw connection where the combination of a low tensile stress in the screw material, a high force acting on the connected parts, and a high temperature causing the connected parts to expand, results in the screw breaking – a scenario that maybe only occurs in 0.1% of all samples. These types of failures are difficult to identify by testing, because the probability of occurrence is relatively low and therefore they tend to occur later in the development process, e.g. during production ramp-up, where volumes are increased and therefore a larger manufacturing variability is experienced or after introduction to the market, where the true variation of use conditions is experienced. At this point, investments have been made in production tools, inventory and assembly equipment, and the costs of design changes are therefore considerably higher.

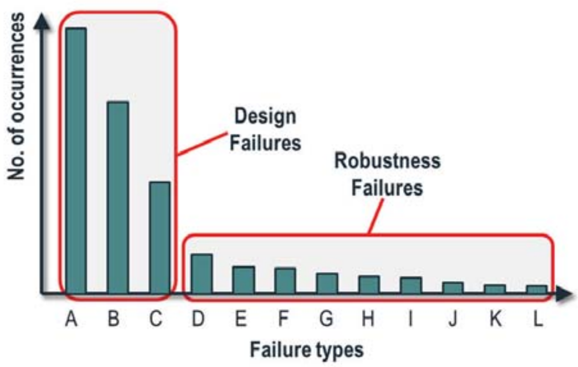


Figure 2 Failures classified by their frequency of occurrence. Robustness failures are difficult to identify, because of the low failure probability.

Robust Design is a collection of methods, tools and principles addressing quality issues related to variation. In Valcon, a consulting company I founded in 2006, together with Janus Juul Rasmussen, we often performed design reviews and design improvements on products that *sometimes* failed and therefore began to investigate the field of Robust Design further to get inspiration and to compare with our own methods and principles for creating *good designs*. We come from a background of moving mechanics and have been schooled on the principles of kinematic mobility and force transmission. Moving mechanics are inherently sensitive to variation if the mechanism concept does not follow specific design rules regarding the degrees of freedom and based on experience, obeying these principles resulted in faster ramp-up times and fewer design changes, not only for moving mechanics, but also for static designs.

At first glance, Robust Design – as it was described in literature – was dominated by statistical methods and focused on analytical methods, whereas our approach was pragmatic and based on design guidelines for achieving a predictable and reliable performance. We also encountered a variety of methods and topics related to Robust Design, e.g. Axiomatic Design, Design of Experiments, Failure Modes and Effects Analysis, Minimum Constraint Design, Design for Six Sigma, Precision Engineering, Variation Modes and Effects Analysis, but it was not quite clear how to combine these methods into a coherent methodology.

Another striking aspect was that despite having a large contact to Danish industry, no Danish companies seemed to know or use Robust Design as part of their development process. Studies confirmed that the industrial adoption of Robust Design is limited, not just in Denmark. In Sweden a survey has shown, that more than 70% of the responding companies do not know what Robust Design is '*at all*', and of the companies that do know what Robust Design is, only 12% use it to '*a large extent*' and more than 35% do not use it '*at all*' (Gremyr et al 2003). Surveys from the United Kingdom (Araujo et al 1996), United States (Thornton et al 2000), and Japan (Fujita 2005) provide similar results. It is not uncommon that the industrial uptake of design methodology is low – but the UK-survey also showed that the *relative* uptake of RD-related methods compared to other design methods is lower, indicating the even method-driven companies fail to see the value in Robust Design.

The surveys also provide an explanation for the low industrial uptake. The respondents argue that Robust Design is too complex to use, focuses too much on statistics, is only applicable by specialists, and is mainly applicable as an optimisation tool late in the design process, where introducing design changes is challenging and costly. A similar critique was put forward by Andersson (1996) pointing out that RD had taken an "unfortunate direction, in that the research (…) had become almost entirely focused on various experimental techniques" and by Mørup (1993), who argued that "Taguchi's methods are applicable only at a late stage of design". From a pragmatic point-of-view, any design tool that is time-consuming will face a challenge of being applied in the early design phases, because the design changes rapidly during these phases, and therefore the results from e.g. a large Design of Experiments analysis may be useless by the time they arrive, because the design has changed while the experiments were conducted.

1.3 Hypothesis and research questions

In conclusion, there is an identified need and a potential for Robust Design in industry, but also a barrier for Robust Design becoming widely accepted and applied due to the complexity and inherent nature of the existing methods and tools that mainly focus on analysis and verification of detailed designs. Indications from industrial consulting projects have shown that an alternative view on Robust Design could contribute to the existing body of knowledge with an approach rooted in the principles from moving mechanics. Based on this, a hypothesis can be formulated. The hypothesis forms the basis of the research and expresses a co-occurrence between two variables (Blessing and Chakrabarti 2009).

Hypothesis
There is a potential for increasing the industrial uptake of Robust Design methods if an implementation strategy is defined and methods applicable at the point-of-design are implemented.

The term 'point-of-design' refers to the situation where the design engineer is sketching a proposed solution, either on a paper/whiteboard or in a CAD-sytem.

The basic **aim** of the PhD-project therefore is, *to consolidate, validate and further develop Robust Design methods in a direction where they become more suitable for industrial application.*
The project scope is further defined by four research questions, which are presented in this section.

The purpose of the first research question is to understand the implications of using Robust Design and thereby enable the definition of success factors for the project. Therefore, the first question is:

RQ1 – What is the impact of Robust Design?

Then it is the aim to establish a baseline in terms of the existing Robust Design methods and compare this to the needs of industry, especially the daily needs of the product development team. This will provide a description of the gaps in the current state-of-the-art as well as a target in terms of criteria that new methodologies must fulfil in order to gain recognition and become widely used in industry. Therefore, the second research question is:

RQ2 – To what extent do current Robust Design methods meet industry needs?

The conclusions from the previous research question define the gaps in current research and lead to the third research question, which attempts to fill the gaps by answering the question:

RQ3 – Which methods, principles and metrics can address the shortcomings of current RDM?

However, the lack of industrial uptake is not just a matter of access to effective methods and principles. Aspects such as change management, creating buy-in from affected stakeholders, adaptation to the context in which a company operates, and definition of roles and responsibilities are also important. The fourth research question therefore asks:

> **RQ4** – How can Robust Design methods become more widely used in industry?

This question specifically addresses the current barriers as well as the solutions in terms of overcoming these barriers. A more detailed description of the applied research approach, including a description of how each question has been addressed in the research, is provided in section 2.

1.4 Outline

The introduction (section 1) contains the background for the research along with the aim and research questions. The research approach is then presented in section 2, which describes the overall research framework as well as the individual research methods that have been applied. In section 3, an overview of selected Robust Design terminology, frameworks and methods is provided as a frame of reference. The results of the research are presented in section 4, as a summary of the five appended research papers with additional research results from studies 2a and 2b (see Figure 4). The conclusion, which is found in section 5, provides answers to the research questions, summarises the main findings, evaluates the research, and discusses the value and limitations of the results. Suggested directions for future research are given in section 6 followed by concluding remarks in section 7, and the references in section 8. Finally, section 9 contains the appended papers.

2. Research Approach

Design science differs from the *explanatory sciences* such as physics and biology both in terms of their purpose and their form. Whereas the explanatory sciences' core mission is to develop knowledge for describing, explaining and predicting the natural world, the mission of design science is to develop knowledge that can be used by professionals to design solutions within their field (van Aken 2005). Therefore, design science has its own set of design research methodologies presented by e.g. Jørgensen (1992) and Blessing and Chakrabarti (2009).

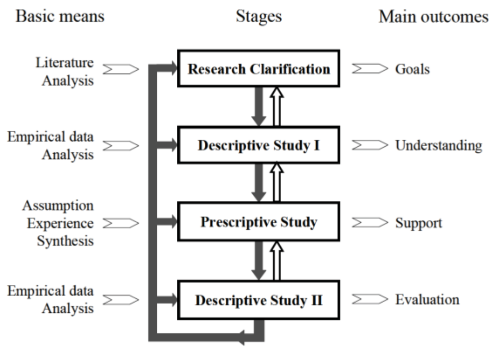


Figure 3 Design Research Methodology framework (Blessing and Chakrabarti 2009)

The approach of the Design Research Methodology (Figure 3) consists of four research stages, each with well-defined means and outcomes. In the *Research Clarification Stage*, an initial description of the existing situation is developed as well as a description of the desired situation, thereby also identifying and selecting the criteria that can be used to evaluate the outcome of the research. The second stage, *Descriptive Study 1*, is used to build a better and more elaborate understanding of the existing situation. This can be done using empirical data, interviews, extended literature studies etc. The following stage, *Prescriptive Study*, develops and defines relevant so-called *support* for creating the transition from the existing to the desired situation. Finally, in *Descriptive Study II*, the impact of the suggested *support* is evaluated by analysing whether the desired situation has been reached.

This project has used the DRM-framework to structure the research activities. The research is therefore divided into the four DRM-stages and in each stage, a number of studies have been carried out to find answers to the research questions stated earlier. An overview of the studies, research questions and publications is given in Figure 4. A detailed description of the activities in each stage is given in section 2.1.

Although the structure of the DRM-model has been used, the research approach has to some extent also been pragmatic by making use of the opportunities appearing during the project as well as accepting challenges and changes to the original plan due to unforeseen events and changed priorities. The DRM-model has therefore been used as a guideline for the research and during the course of the project, the research plan has continuously been updated to reflect the changes in the project.

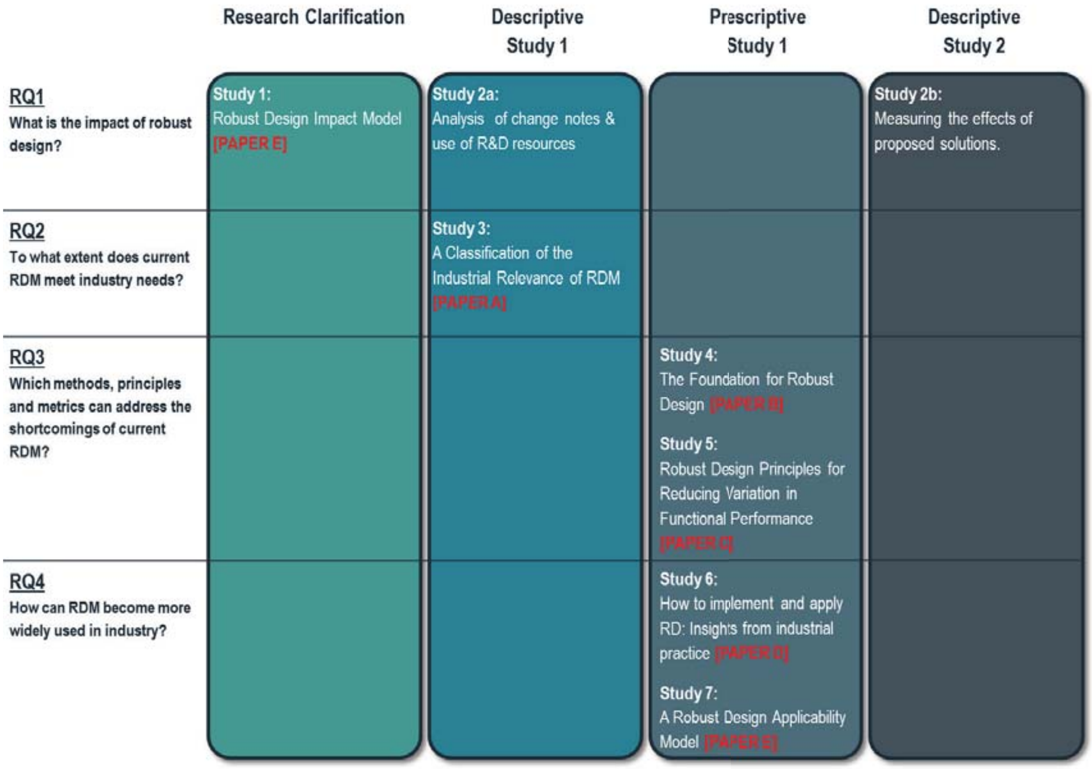


Figure 4. The Design Research framework. The research has been structured in four stages (main studies), each encompassing one or more sub-studies, aimed at answering the four research questions.

2.1 Research Stages

In this section, the studies related to the four research stages are described. The results of all studies can be found in the appended research publications, except for study 2, which is presented during the results section. .

2.1.1 Research Clarification

The purpose of the Research Clarification was to strengthen the initial assumptions and indications that there was a need as well as a potential for an applied version of Robust Design with an improved level of industrial support. Literature was investigated to gain a more elaborate understanding of the existing research within the field. The study was especially focused on the available methods, tools and principles and the effects of applying them in an industrial context. In its pure form, a robust design is a design that is insensitive to variation. An objective of the Research Clarification phase is to clarify how the initial factor impacts other factors, eventually ending up with the profit of the organisation. Based on the initial literature study combined with an analysis of industrial cases from Valcon, a draft impact model was defined, identifying the causal factors linking *sensitive designs* to *company profit.* The impact model was used to identify parameters and metrics by which the effect of Robust Design could potentially be measured.

2.1.2 Descriptive Study 1

The purpose of Descriptive Study 1 was to gain in-depth knowledge about the existing Robust Design methods and to understand the reasons why they were not being applied.

A case study was conducted to document and quantify the experiences from industry where the impression was that companies struggle with production ramp-up due to quality issues late in the design process. The case study was carried out in a Danish consumer electronics company that I had worked with previously as a consultant. The company was selected based on its development speed, which made it possible to potentially run several case projects within the timeframe of the research project, and the type and level of complexity of the products, which are largely mechanical products with typically 100-500 components. As criteria, two impact factors from the impact model were chosen, namely the misapplied R&D resources and the late stage design changes. These were chosen as classic symptoms of non-robustness and an analysis of historical data from the case company's time registration system and change request database was carried out to define a baseline in terms of recent performance

In addition a more thorough literature study was performed, aimed specifically at classifying the existing Robust Design Methods against a set of defined industrial needs. This study is reported in Paper A. The study also included analyses and reflections on how the variety of methods and tools within quality engineering are related to each other.

2.1.3 Prescriptive Study

The purpose of the Prescriptive Study is to present *support* that can create the transition from existing to the desired situation. The support that has been developed The study used different approaches depending on the type of proposed solutions:

- **Specific design principles and metrics.** Direct support to the design engineers was developed by combining existing principles from a variety of theories, such as Axiomatic Design and Kinematics as well as design guidelines from precision engineering and mechanism design. The development was a collaborative effort with chief-engineers at Valcon and has been through several iteration cycles with development, application on an industrial consulting case, and evaluation of usability and applicability. The results are presented in Papers B and C.

- **Implementation archetypes.** Support on the organisational level, describing how to define, deploy and drive robust design in an organisation was developed using interviews of quality managers and R&D Directors in four international companies already applying Robust Design. For two of the companies, the interviews were supplemented with research publications describing how the companies used Robust Design, and for the two remaining companies, supporting knowledge on the implementation was available to the authors due to ongoing work and research activities within the companies. The results of the study are presented in Paper D.

- **An Applicability Model.** In addition to the support on *what* (principles and metrics) and *how* (implementation archetypes) to use Robust Design, it is beneficial to also assess the relevance of applying Robust Design. This support – the so-called Robust Design Applicability Model – was developed using an analysis of case studies. Information about the cases was available either through direct involvement or by interviewing the project managers that had driven the projects. The results of the study are presented in Paper E.

2.1.4 Descriptive Study 2

The purpose of this study is to evaluate the application and impact of the *support (principles/metrics, implementation archetypes, and applicability assessment)* proposed in the Prescriptive Study, such as suggested in the DRM-model (Blessing and Chakrabarti 2009).

The **evaluation of the support** is done by measuring the suggested principles and methods in terms of their:

1. **Usability** – is the *support* understood and usable by the intended users
2. **Applicability** – does the *support* address the key impact factors identified in the Impact Model

The **evaluation of the success** in design science can prove more challenging than in the explanatory sciences (where experiments are used to verify the validity of a model or hypothesis), for several reasons, e.g.noise factors (influence from other factors) (Pedersen 2009), statistical uncertainty (few data points), and comparability (design projects vary in size and nature). However, to measure the success of the proposed support, success criteria were selected from the impact model. The selected success criteria were chosen based on their level in the impact model (pro*fit of the company* is the ultimate impact factor, but this is affected by a large number of underlying factors, and is therefore not suitable for research verification) as well as the ease of access to both new and historical data, which would be necessary to make a comparison between performance before and after the introduction of the new design methods. Ultimately, the '*Use of R&D resources before and after design verification' and the 'Number of change requests' were* selected as the measurable criteria. These data were derived from a variety of projects which had been completed recently. The proposed support was implemented through training, an update of the development manual and ongoing sparring with the project's key members and afterwards, the same data were derived and compared with the historical performance.

2.2 Additional research activities

Apart from the literature studies, case studies, and interviews already mentioned, the research has also involved additional activities that indirectly contributed to the results. These activities include:

- Taking **courses** has given specific insight into e.g. statistics and teaching and learning methods

- Attending **conferences** has given inputs from state-of-the-art research as well as feedback on the presented papers.
- Hosting **workshops** has contributed with interesting discussions with international researchers and engineers.
- **Co-authoring** papers with international researchers has given constructive critique of methods and results and allowed benchmarking with international research and industrial best-practice.
- Robust Design **Training** in industry and academia has forced the research results to be kept in a conveyable format, which are directly applicable in an industrial context. It has help secure the usability and applicability of the proposed solutions.
- **Supervision of student projects** has contributed by allowing the exploration of related, but not necessarily central elements of the research field.
- **Consultancy work** done in parallel to the research has acted as a test-bench for obtained results and has provided many ideas, observations and feedback. One project of particular importance was the development and implementation of Robust Design in a large Danish medical device company with 300+ mechanical engineers. The company is used as one of the four cases in Paper D, where details regarding the training, roles and responsibilities and way of working with Robust Design can be found. The importance of simplicity, speed, usability and applicability of design methods was underlined along with the need for proper change management.

3. Theoretical Basis

The purpose of this section is to describe the theories, methods, and frameworks that form the theoretical foundation for this research. It is not the intention to present a complete description of every publication ever written about robust design, but rather to convey a selected extract of methods and theories that are directly relevant to this research. The section is divided into four sub-sections. First, the main terminology is defined to ensure a common understanding of the subsequent subsections, in which the first theories, then frameworks, and finally methods related to Robust Design are presented.

Theories related to the research:

- Design Process Theories
- Quality Loss Function
- Axiomatic Design
- Transfer Function

Frameworks related to the research:

- Taguchi Methods for Robust Design
- Variation Risk Management
- Robust Design Methodology
- Design for Six Sigma
- Variation Management Framework

Methods related to the research:

- Minimum/Exact Constraint Design, Kinematic Design, Location Schemes, Design Clarity
- Failure Modes and Effects Analysis
- Variation Modes and Effects Analysis
- Fault Tree Analysis / Event Tree Analysis
- Design of Experiments / Monte Carlo Analysis / Sensitivity Analysis
- P-diagrams / Quality Function Deployment / Fishbone Diagrams
- Process Capability Databases

3.1 Terminology

To avoid misunderstandings and to enhance the understanding of the subsequent description of theories and methods, a basic definition of main terminology related to Robust Design is presented in Table 2. In some cases, the terminology used in research differs from the terminology used in industry. In these cases, the terminology used in industry is preferred, as one of the main aims with this thesis is to define how Robust Design should be applied in industry.

Table 2 Terminology related to the research

Term	Description
Product	In this research, the word product is used to describe a technical system (Hubka & Eder 1974; Andreasen 1980). This research is delimited to dealing only with mechanical and electromechanical products. The term product is not confined to mass-produced consumer products, but can also include e.g. machines and process equipment.
Function	A product fulfils a purpose that can be described by its functions (Eder et al 2008). A product can have multiple functions and each function can comprise several sub-functions.
Functional performance	Functions can be described be their behaviour (Vermaas 2013). Physical attributes such as forces, displacements and sound levels can be used to define the intended behaviour – or performance – of a product, as well as the allowable deviation from this intent (specification limits). In some frameworks, the term Key Performance Characteristics is used, which can be any quantifiable feature of a product whose expected variation from target has an unacceptable impact on the product. (Thornton 1999)
Failure	The term failure is not uniquely defined in literature. In reliability engineering, failures are sometimes defined as *the termination of the ability to perform a required function*. In robust design, a failure can be seen as *a situation where the product operating outside its specification limits*, meaning that the product may still be operational, but it performs unsatisfactorily.

Variation The Theory of Properties (Tjalve 1979) states that a technical system is determined by five properties: Structure, shape, dimensions, material, and surface quality. These properties are subject to variation due to e.g. manufacturing variability (tool wear, multiple-cavity tools, material batch properties, etc.) and use conditions (temperature, humidity, forces from the user etc.). Variation can occur within the same sample over time, or from sample to sample. Variation of properties can lead to variation in behaviour or performance (see section on Transfer Functions below). Goh (2002) states that "All quality problems during the generation of goods and services arise fundamentally from only one cause: variation. If there were no variation in the real world, there would have been no quality problems at all, since every unit of goods or every offer of service would be of exactly the same predictable characteristics." Different categorisations of variation exist, but the content is quite similar (Bergman et al 2009). Taguchi (1986) makes a distinction between control factors (variation that can be controlled e.g. dimensions on a drawing) and noise factors (variation that cannot be controlled, e.g. elongation due to temperature). Clausing (1994) defines three classes of variation: variation in conditions of use, production variations, and deterioration.

In this research, six types of variation that can affect the performance of a product are used:

1. **Manufacturing Variability** – e.g. from tool wear or multiple cavity tools
2. **Assembly Variability** – e.g. from part float
3. **Load Variability** – e.g. due to user input forces
4. **Variability due to ambient conditions** – e.g. due to changes in temperature
5. **Variability due to time** – e.g. from material creep
6. **Variation in material properties** – e.g. from variations in alloy compositions

Quality In our everyday language, product quality is used interchangeably to refer to products with an extensive set of functional features, products with high durability and long life-time, products with the 'right' look and feel, and products with a behaviour living up to the expected specifications. Mørup (1993) defines quality as "the customer's experience (or perception) of how well the totality of quality properties of a product satisfies his stated or implied needs". This research does not provide a distinct quality definition but limits the scope to aspects of quality that are controlled by the design engineer. This means, that the definition of product specifications and *product profiles* that describe the target product is not discussed (as these are seen as belonging to a separate discipline controlled by marketing specialists and industrial designers). Instead, quality is primarily seen as continuously performing as close as possible to the intended nominal performance.

Reliability	Reliability can be defined as 'the ability of an item to perform a required function under stated conditions for a specified period of time.' (ISO 8402). Reliability is seen as a function of robustness in the sense that a robust design will have consistent performance regardless of any parameter variation and therefore stand a better chance of performing its required function (as stated in the definition of reliability).

3.2 Theories related to the research

Ullman (1991) states that a Design Theory can have one of three different foci. First, they can be formulated to explain the designed object itself, i.e. how the object comes into being and evolves into a final, manufactured product. Second, theories can be formulated to explain how the designer(s) transforms an ill-defined problem into a fully described product. Finally, theories can be developed that attempt to explain the process of design, the interaction of the artefact and the people and/or computers in the design environment. In addition, Andreasen et al (2014) define Model-Based Theories as design theories where underlining that the core of the theory is a modelling of artefacts based upon a selection of concepts and mental constructs. The theories presented in this section fall into at least one of these categories.

3.2.1 Design Process Theories

Production companies develop new products using more or less formalised design processes, depending on the context and corporate culture. A variety of design process theories have been presented by e.g. Pahl and Beitz (2007), Andreasen and Hein (2000), and Ulrich and Eppinger (2012). Although they differ slightly, the design processes have in common that they describe a set of stages leading from the initial *product idea* to *running production,* describing the activities and deliverables for each stage (see Howard et al (2008) for a complete review of design processes and their stages). In reality, the design process is less linear, due to e.g. reuse of components from existing products, frontloaded development of critical functions, and loop-backs due to unsatisfactory performance, which means that certain parts or modules in the design may be more mature than others.

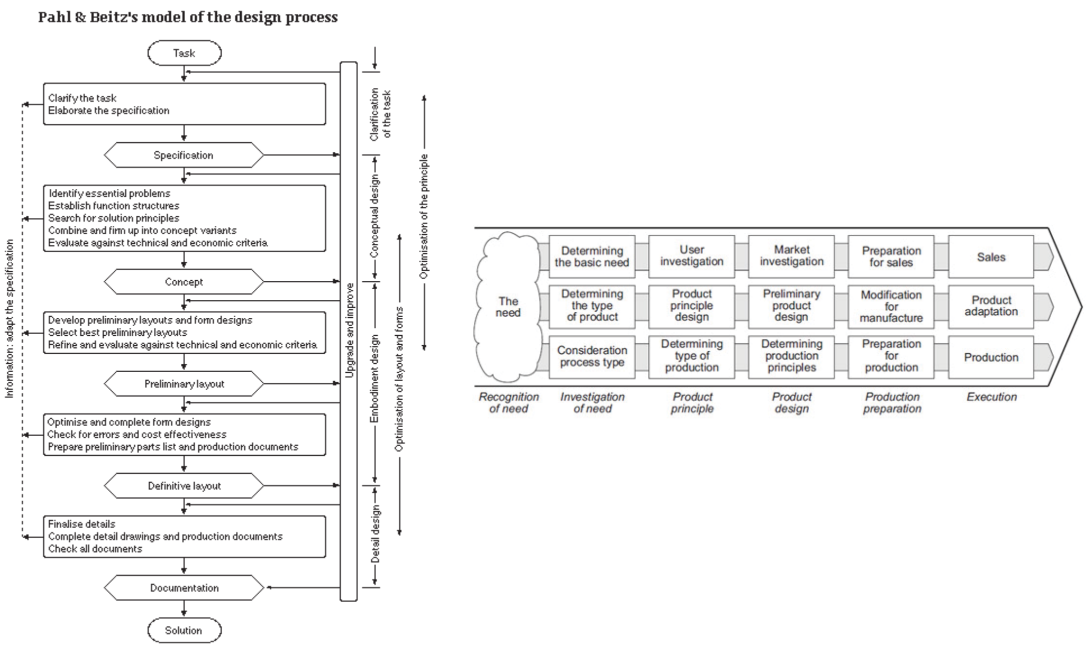


Figure 5 (a) The design process presented by Pahl & Beitz and (b) the Integrated Product Development Process proposed by Andreasen and Hein.

Relevance for this research:

Design Process Theories are relevant to this research because Robust Design is not seen as a stand-alone process, but rather an integrated part of a generic product development process. It is therefore relevant to discuss where in the design process, the various robust design activities should be placed, how they interact with the generic activities of the design process, such as sketching, conceptualisation, detailing etc. and also how they trade-off against or complement other Design for X (DfX) approaches.

3.2.2 Quality Loss Function

Traditionally, the understanding of quality is confined to keeping the functional performance of the product within a set of given specification limits. In this understanding, any performance within the specification limits is assigned an equal value to the user and any performance outside the specified limits is seen as a constant loss. This approach is supported by quality inspection using e.g. gauges and pass/fail testing.

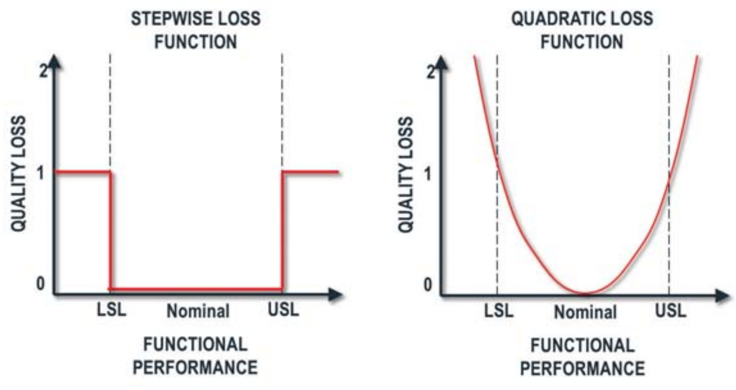


Figure 6 The quality loss function seen as a stepwise function (left) and a quadratic loss function (right).

The stepwise loss function is very suitable for inspection purposes, as it defines a specific acceptance limit, but it does not necessarily reflect the user's perspective in all cases. Consider the force to activate a ball point pen, which may have a functional requirement stating that it should be 3±1N. In the stepwise understanding of quality loss, any performance between 2N and 4N is equally good, and any performance outside this range would be perceived as a constant loss. In reality, the average user may find a force of 3N to be preferable and as the actual performance deviates from this, the user gradually experiences a quality loss. At a certain point the force may become so high that the user cannot activate the pen or so low, that the pen is activated by mistake inside a pocket or bag, both of which would constitute a significant quality loss, but the pen is still fully functional. To express this Taguchi (2005) argued that the quality loss can be quantified and given specific monetary values representing the loss to society as the product performance deviates from nominal, such as shown in Figure 6. Taguchi has also expressed this as: "You gain nothing in shipping a product that barely satisfies corporate standards over one that just fails."(Taguchi 1990). A popular case study reported by Phadke (1995) shows how customers perceived the quality of television sets produced at two different production sites differently, even though they all fulfilled the product specifications. It turned out that the Japanese production site strived to reach nominal performance, whereas the American site focused on fulfilling requirements and as a result the average performance of the Japanese television sets was much closer to nominal performance.

Taguchi also presents mathematical expressions for quantifying the actual quality loss to society, as performance deviates from nominal. However, it is my opinion, in line with e.g. Goh (2002), that this would require a more precise definition and delimitation of 'loss' to be valid. In the current definition it is not clearly specified how to include loss in brand value, lost future sales etc. Furthermore, a substantial effort to gather the relevant information to calculate the loss functions for all functions in a product is required. Examples of successful derivation of quality loss functions have been demonstrated, e.g. for the visual appearance of a product and for split lines in mobile phones and cars (Wagersten et al 2007, Huittinen 2015, Forslund et al 2006), and for functions related to audio (Boegedal et al 2015) and tactile preferences. In recent work (Pedersen et al 2015), incorporates quality loss functions into requirements specifications, which enables the design engineer to take more informed decisions on trade-offs where two functional requirements are in opposition to each other.
From a practical point of view, the distinction between the two quality loss definitions is mainly relevant for prioritisation of the robust design tasks. Obviously, the main focus should be on functions that have a steep gradient on the quality loss curve *and* a large variation in performance.

Relevance for this research:
The Quality Loss Function is relevant for this research because it is the starting point for understanding how variation in performance is related to the perceived quality of the product. It is also a central part of prioritising Robust Design activities on functions with the largest expected quality losses (steep gradient on the quality loss curve combined with a large variation).

3.2.3 Transfer Function

The Transfer Function is central to the concept of Robust Design and it links together the theories and methods of the field. In its pure form, the Transfer Function is a mathematical representation of the relationship between the functional performance of a design and the design parameters that influence this performance. The function uses Design Parameters such as dimensions or material properties as input variables and relates these to the behaviour of the product, called the Functional Performance.

On a graph of the Transfer Function, the gradient represents the sensitivity of a function to a change in a design parameter, in other words its robustness. The shallower the gradient the more robust and less sensitive a functional performance is to changes in the given design parameter. If the expected variation of a design parameter is known or can be assumed by using e.g. process capability databases (Tata et al 1999; Okholm et al 2014), the functional performance of the product can be predicted and expressed as a probability distribution, such as shown in Figure 7.

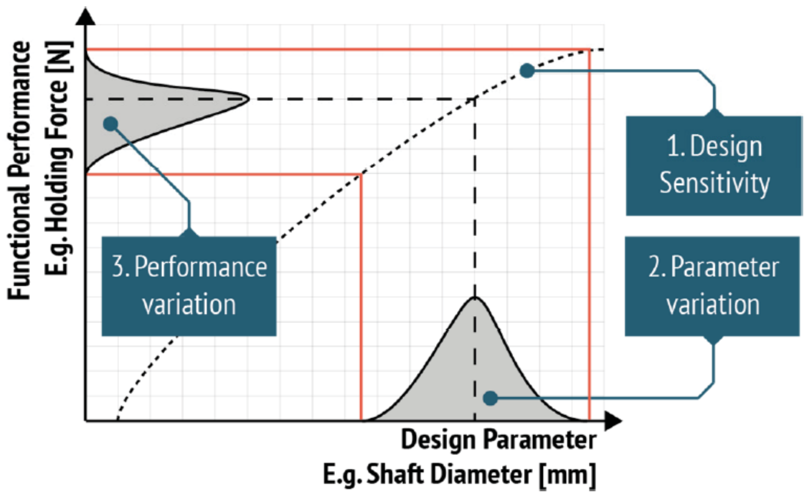


Figure 7 The Transfer Function expresses the design's Functional Performance as a function of a given design parameter.

The objective for the design engineer is to minimise the variation in Functional Performance. This can essentially be done in two ways: 1) Reduce parameter variation. However, not all types of variation can be controlled and at certain limits, the cost of attempting to reduce incoming variation increases significantly (Booker et al 2001) (e.g. by adding or changing to more precise machining processes). 2) Reducing design sensitivity which can be achieved in different ways:

1. By **changing the design concept**, an entirely different Transfer Function is defined with different design parameters and sensitivities and therefore also a different variation in Functional Performance. This enables a comparison of multiple design suggestions and selection of the most robust design based on the variation in Functional Performance. In Figure 8, two design solutions, a screw and a snap-fit, are presented for constraining a component, A, in a product. The functional requirement is that A must maintain its position, when a force, F ,is exerted. The two solutions have different transfer functions each of which has its own set of design parameters.

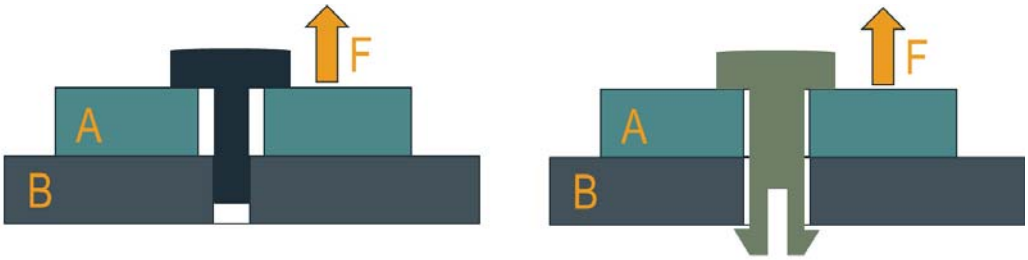


Figure 8. Two solutions for constraining a component A. Each solution has its own Transfer Function(s).

2. By **optimising the design parameters** non-linearities and sensitivities can be used to reduce variation in Functional Performance. Figure 9 illustrates a design in which a pointer is constrained by two components with heights h and t. The functional requirement for the design is to position the pointer accurately on a scale. The position of the pointer is defined by the parameters a, b, h and t. Intuitively, design B is more robust, because it is less sensitive to the variation of the parameters h and t.

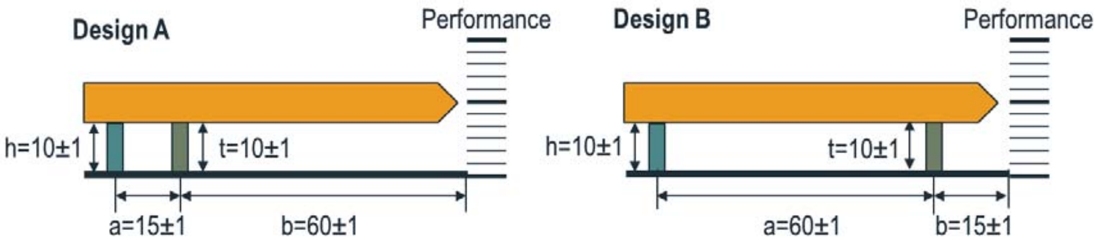


Figure 9. The objective of this design is to position a pointer on a target. The pointer is constrained by two components with the heights h and t.

The Transfer Function is very widely used in literature, but for describing an actual mechanical design it can be somewhat misleading as it gives the impression that Robust Design is merely an optimisation exercise with the objective of adjusting the values of the design parameters to mathematically obtain the most robust design.

In reality, the Transfer Function is challenging to use for several reasons, which are listed below. To illustrate the different points, a simple case of a press-fit connection is used (Figure 10). The two most relevant functional requirements for a press fit are the holding force (the force holding the two parts together) and the stress level (which should be below the yield stress of the materials used). The challenges – even for such a simple case – include:

- The functional performance may be a function of not just one, but several design parameters. The press fit holding force is a function of (at least) ten parameters, as seen in the formula for the holding force. The overall probability distribution of the holding force is a function of parameter variation and design sensitivity for *all* of the underlying design parameters.
- A design parameter can affect multiple functional performances. This is called a coupled design and is explained in more detail under Axiomatic Design. In the press fit, the diameter of the mating surfaces controls both the

holding force and the stress. This limits the freedom of choice as the optimal value of the parameter may not be the same for both functional requirements.

- Design parameters can be coupled indirectly. In the press fit, changing the elasticity modulus can only be done by changing materials, which inherently may also change the Poisson's ratio, which is also a design parameter.
- It is up to the design engineer to identify the relevant design parameters and to decide on the level of granularity of the derived Transfer Function. For the press fit, parameters such as surface quality and residual stress from manufacturing have been filtered out, e.g. because their effect has been seen as negligible, but in cases where an analytical expression is not given, the identification of relevant design parameters is a task for the design engineer.
- Unless an analytical expression is given or can be derived (e.g. the formula for a screw connection or a press fit), deriving the transfer function by simulations and/or testing can be both time consuming and challenging (Eifler et al 2011) For the press fit, analytical expressions were available for both the holding force and the stress level requirements.

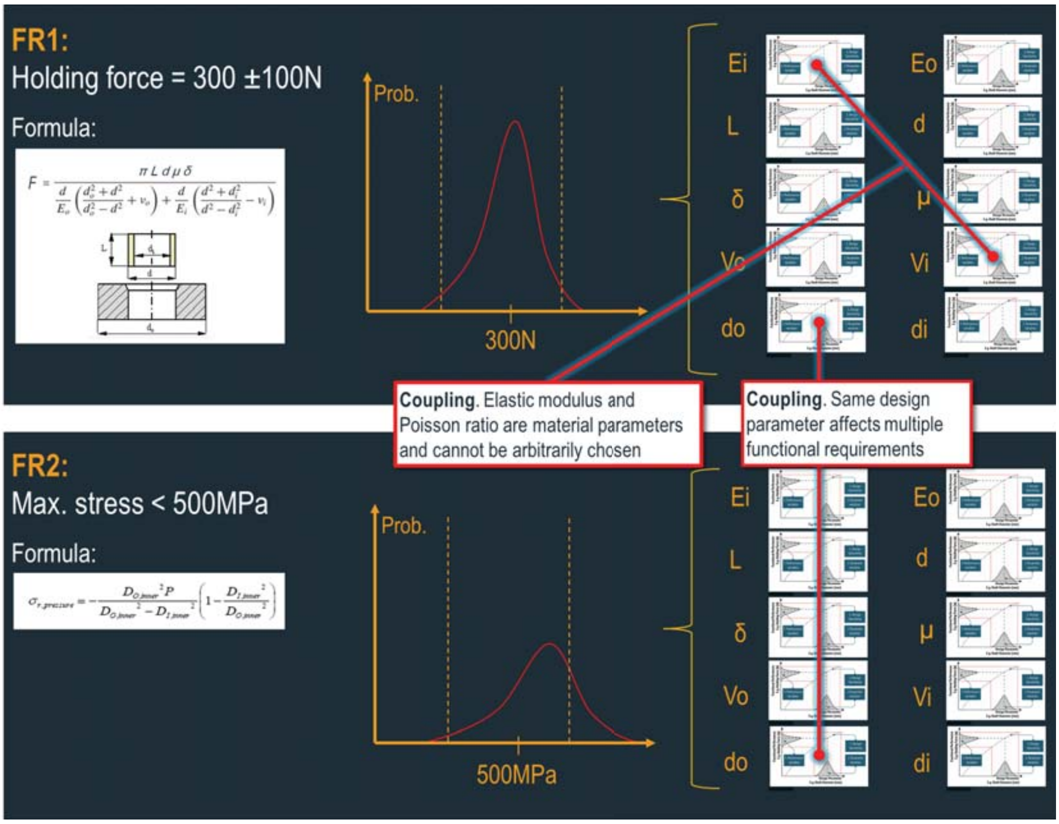


Figure 10. A design has multiple functional requirements, which in turn have multiple design parameters. Couplings can exist between design parameters as well as between functional requirements.

The main contribution of the Transfer Function is seen as its illustration of design sensitivity and the two principle ways of handling the influence of variation on product performance. This division reflects the typical division of tasks in production companies, where the production department focuses on reducing parameter variation and the design department focuses on reducing the sensitivity of the design. It is important to maintain focus on both aspects for optimal results. In everyday design situations, its value is limited, because of the number of functions, subfunctions and design parameters of typical products.

Relevance for this research:
The Transfer Function is regarded as *the* central element in Robust Design Thinking and has been used in the appended papers to position and classify various Robust Design Methods. It is also central in understanding how the complexity and variation in functional performance can be brought down by reducing the number of design parameters that control a given functional performance.

3.2.4 Axiomatic Design

Axiomatic Design was first proposed as the Principles of Design (Suh 1990) followed by Axiomatic Design. The Advanced Formulation (Suh 2001) makes the provocative claim that underpinning engineering design there are just two fundamental axioms (self-evident truths):

Axiom 1: **The Independence Axiom**. Maintain the independence of the functional requirements (FRs).
Axiom 2: **The Information Axiom**. Minimise the information content of the design.

Axiomatic Design also maps the links between Customer Attributes (CA), Functional Requirements (FR), Design Parameters (DP), and Process Variables (PV), thereby defining four domains (Figure 11). The axioms apply to the mappings between each domain and it important to note that variation can be experienced in all of the four domains.

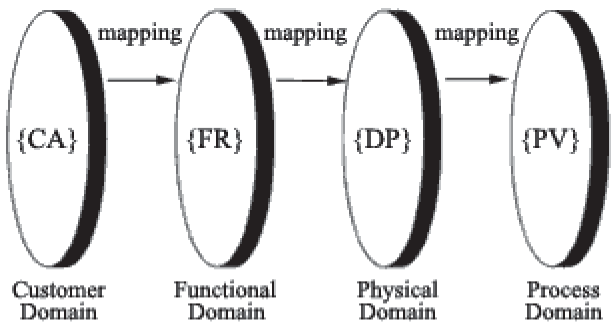


Figure 11. The domains of Axiomatic Design presented by Suh (

Figure 11 describes the simplest form of relation between the four domains where each domain only has a relationship with (or through) the domain next to it. The figure also makes the simplification to one dimension, showing how one CA maps to one FR to one DP and one PV. However, products do not have such a one-dimensional relation and in reality a hierarchical structure as shown in Figure 12 should be used to describe the domains.

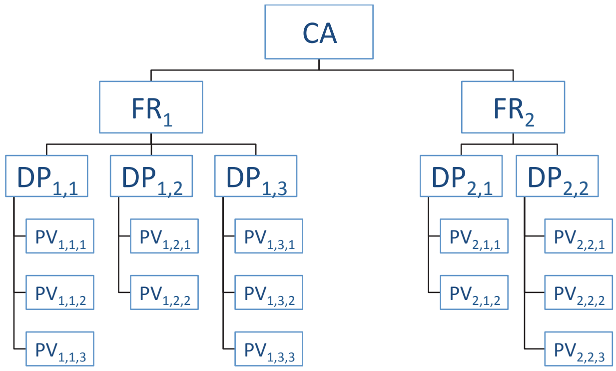


Figure 12. The hierarchy of domains in Axiomatic Design

The value of Axiomatic Design lies in its illustration of how variation propagates through the four domains and its description of how couplings and unnecessary information presents a challenge for controlling and reducing variation in functional performance. As for the Transfer Function, the value in everyday use is limited due to the many functions, subfunctions and design parameters in typical products. As an example, on an insulin injection device, the dose activation force (the force required to trigger the device into delivering the drug) is a function of 118 design parameters and the practical issues concerning the identification and continuous management would pose a huge task.

Relevance for this research:
Axiomatic Design is used as a means to describe the complexity of product development by illustrating the vast number of design parameters and couplings that exist between the four domains. Axiomatic Design is also used to argue why kinematic design is an essential step to reduce product complexity, as it eliminates unnecessary design parameters, hence reducing the level of information in the design (Axiom 2).

3.3 Frameworks related to Robust Design

Perhaps the best way to define a framework is in terms of its relation to a model. According to Macmillan et al (2001) a model is defined as a simplified representation of a system or complex entity. A framework is therefore a structure in which the design related models can be positioned relative to one another in a meaningful way. For the purpose of this thesis the definition of a framework is expanded to structure that is also able to position tools and methods related to robust design.

3.3.1 Taguchi Methods for Robust Design

It is virtually impossible to discuss Robust Design, without also mentioning Taguchi Methods. Taguchi (1986) suggests a three-stage process for obtaining a robust design: System design, Parameter design, and Tolerance design. System design is the conceptual design of the product, including determination of functions, principle solutions, part structure, etc. Parameter design is the optimisation of design parameters using e.g. non-linearities in the transfer functions, such that the variation in Functional Performance is reduced. Finally, Tolerance Design uses design sensitivity to assign tight tolerances to sensitive parameters and loose tolerances to robust parameters.

Relevance to the research:
The Taguchi Methods have been used as a starting point for the research and been used to identify potential improvement areas. The first stage, System Design, was found to be less specific than the two subsequent stages, which is inline with the general critique that Robust Design does not support early-stage design.

3.3.2 Variation Risk Management

Variation Risk Management (VRM) is a framework proposed by Thornton (2004). VRM consists of three stages: identification, assessment and mitigation. In the identification stage, system requirements that are sensitive to variation are identified and decomposed into subsystem, feature and process characteristics that contribute to the system variation. In the assessment stage the key characteristics are prioritised based on the expected variation and cost, because in most cases, it is not feasible to work with all of the identified key characteristics due to limited resources. In the final stage, sources of variation or their impact on the design are reduced. Each stage comprises a number of methods to support the activities, including Quality Function Deployment, Design of Experiments, Failure Mode and Effects Analysis, etc.

Relevance for the research:
VRM contributes by taking the fragmented toolbox with methods and theories related to variation and robustness, and stiches these together to a more coherent process. It includes not only the core of robust design thinking, but also taking into consideration which key characteristics are relevant to prioritise and how these are identified. VRM includes more of the managerial aspects on how to apply not only the core Robust Design methods, but also the practical sides of industrial application, where resources are limited.

3.3.3 Robust Design Methodology

Robust Design Methodology presented by Hasenkamp, Gremyr and Arviddson (Hasenkamp et al 2009; Gremyr et al 2011) categorises and structures Robust Design into Principles, Practices, and Tools. Principles are defined as the underlying reasons for why Robust Design should be applied and Tools comprise the suite of RD tools such as Design of Experiments, Transfer Functions, etc.

Principles (Why to work with RDM?)	**Practices** (What to do for RDM?)	**Tools** (How to do it?)
Awareness of variation (is the basis for systematic robustness efforts)	Focus on the customer	QFD, design reviews, VMEA, brainstorming, cause-effect diagram, flow chart, ideal function
	Identify and understand noise factors	Mathematical modelling, empirical correlations, designer intuition, simulation
	Check the assumptions (*e.g.* const. error variance or const. % error)	Experience and prior knowledge
Insensitivity to noise factors (is the ultimate goal)	Exploit nonlinearities and interactions	Design of experiments, simulation, transfer function, error transmission formula
	Design for insensitivity to noise factors	Smart features, brainstorming, design by analogy, checklists and patent literature, TIPS, literature lacks design synthesis tools
	Use conventional design rules	Experience and prior knowledge
Continuous applicability (to take all opportunities for robustness improvement)	No practices in terms of activities → organisational aspects affecting continuous application	Integration of RDM into the development process (vs. separate robustness improvement projects)

Figure 13. Design Research Methodology structures Robust Design into principles, practices, and tools.

Relevance to the research:
RDM has been used as a classification framework, to distinguish between the purposes of the various RD methods. Furthermore, RDM points at research gaps such as the lack of design synthesis tools. The use of 'conventional design rules 'and 'experience and prior knowledge' has been a central aspect of this research as the presented principles and methods elaborates upon these tools.

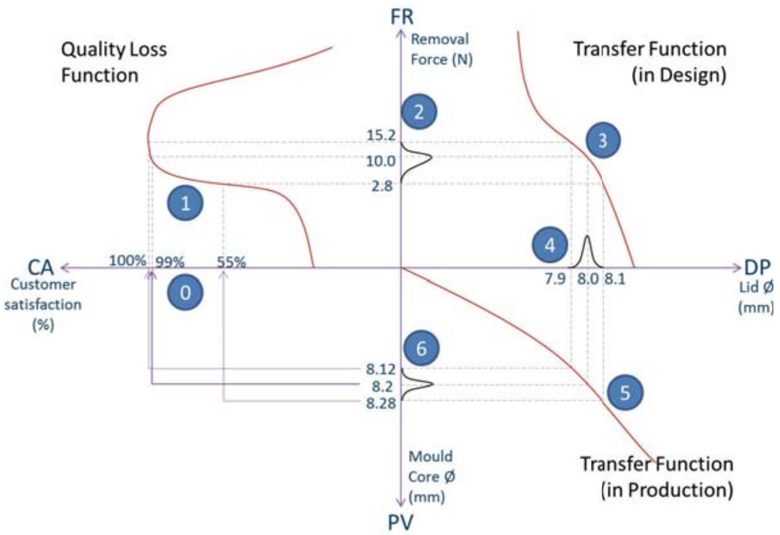
3.3.4 Design for Six Sigma (DfSS)

Design for Six Sigma is a framework that has gained popularity in industry in recent years. Design for Six Sigma differs from the original Six Sigma by being applicable to processes and designs being built from the ground-up, where Six Sigma is applied to existing processes and products. DfSS is not uniquely defined, but is rather a collection of suggested approaches. The approaches differ to some extent, but have in common that they comprise a set of predefined phases that form an acronym by which the approaches are named, such as DCCDI, DMEDI or IDOV, where e.g. IDOV means: **I**dentify specifications, **D**esign the solution, **O**ptimise the performance, **V**alidate the result against specifications. DfSS suggests the use of specific robustness and reliability tools for various phases, e.g. Quality Function Deployment, Design of Experiments, Taguchi Methods, etc.,

Relevance for the research:
The value of DfSS lies in the way it structures Robust Design (and other) activities into an ordered process and is therefore related to the VRM. However, it does not present any new tools.

3.3.5 Variation Management Framework (VMF)

The VMF uses the concept of the quality loss function and the transfer function to represent variation across the four domains proposed in axiomatic design. The objective of the framework is to explain and visualize how variation propagates from one domain to the next. The VMF consists of three main quadrants linking the four domains of axiomatic design (labeled on the axes), as shown in Figure 14. The fourth quadrant can be seen to represent trade-offs between production process investment and quality loss. The figure shown uses estimated data and relationships to populate a VMF modelling the pull off force required to remove a pen lid. Marked onto the model are 7 blue circles indicating the positions where the project manager has the opportunity to invest in quality improvements.



No.	Quality Improvement Strategy
0	Accept variation in the marketplace
1	Reduce sensory/perceptual robustness (perhaps add more tactile features to lid)
2	Reduce outgoing variation by increasing outgoing quality control (product sampling)
3	Reduce the sensitivity of the design
4	Reduce ingoing variation by increasing ingoing quality control (part measurement)
5	Reduce production sensitivity (design of experiments)
6	Reduce production variation (iteration and re-working of moulds)

Figure 14 The Variation Management Framework (Howard et al 2014)

The Variation Management Framework was first described by Howard et al (Howard et al 2014) and is now in the process of submission to the journal Total Quality Management and Business Excellence. The VMF ties together the individual and uncoupled methods of Robust Design and therefore contributes to the classification and positioning of both existing and new methods, but it differs from the other frameworks described in this section as it does not define a specific order of activities or any managerial aspects of Robust Design.

Relevance for the research:
The VMF has been defined in parallel with the research presented in this thesis and it has supported the understanding and classification of Robust Design methods.

3.4 Methods related to the research

Robust Design comprises a variety of tools and methods. A selection of the methods that are relevant to this research are briefly described below, along with a description of their relevance to the research.

- **Minimum/Exact Constraint Design, Kinematic Design, Location Schemes, Design Clarity**

A variety of methods focus on creating interfaces between products, with only the necessary set of contact points. The principle is presented in different forms, e.g. as Minimum Constraint Design (Hale 1999), Location Schemes (Söderberg et al 2006), Design Clarity (Bertsche 2008) and Kinematic Design (Whitney 2004). The underlying principle of these methods is to detect and avoid overconstraints between parts. Overconstraints result in ambiguous load transmission paths, unclear tolerance chains, internal stresses in the parts, and a loss of predictability in functional performance. These methods form a central part of this research as they accommodate some of the critique of other Robust Design methods by being simpler to use and can also be translated into design guidelines, rather than only acting as analysis tools. In the following, this set of methods will be referred to as Kinematic Design.

- **Failure Modes and Effects Analysis (FMEA)**
  FMEA (Stamatis 2003) was developed in the aerospace industry in the 1960's to support the Apollo missions. In the 1970's the automotive industry also began using FMEA and it has now become a de facto standard in not only automotive, but also the medical device industry, where the use of FMEA is often part of the contractual obligations for sub-suppliers.
  FMEA is used to manage and prioritise risks in the design, by identifying possible failure modes, and hence assessing the probability of the failure happening, the severity of the failure if it happens, and the probability of detecting the failure. The assessment results in a Risk Priority Number (RPN) for each failure mode, which can be used to prioritise and address the risks. FMEA is relevant to this research because it is probably, along with Design of Experiments, the most often mentioned method in Robust Design literature. However, FMEA also has its limitations. The ratings of severity, occurrence and detection are typically subjective and measured on a '1-10 scale' and therefore may not be accurate. Furthermore, because the failure modes are identified by an FMEA-team, the quality of the FMEA-process relies on the competencies of the team and their ability to conceive expected failure modes.

- **Variation Modes and Effects Analysis (VMEA)**
  The VMEA (Johansson et al 2006) identifies key performance characteristics (KPCs) of the product and hence assesses the expected variation of parameters controlling the KPC as well as the KPC's sensitivity to variation. The assessment is done on a 1-10 scale and the result of the VMEA is a structured and quantified list of the contribution of each of the sub-KPCs to the main KPC. The VMEA can be described as a pragmatic alternative to the more formalised Design of Experiments, because it is simpler and faster to use, but obviously lacks the precision of the DOE. The VMEA is relevant to this research because it, due its pragmatic approach, is suitable for application in an industrial context and does not require in-depth statistical knowledge to be used.

- **Fault Tree Analysis / Event Tree Analysis (FTA / ETA)**
  If the performance of a given component or module is well established or can be meaningfully quantified, mathematical and statistical models can be used to model the system and predict its reliability. Examples of this include electrical components such as transistors and standard mechanical components such as pumps or bearings. By combining Boolean expressions and probabilities, the probability of failure for the system can be calculated. FTA/ETA (Lee et al 1985) are primarily used for risk management on large systems such as power plants. The methods are often mentioned in Robust Design literature, but are not seen as central to this research, because from a product development perspective, parts are typically custom made and therefore cannot be meaningfully assigned a numerical reliability.

- **Sensitivity Analysis**
  The overall variation in Functional Performance as well as the sensitivity of the underlying design parameters can be identified in a number of different ways:
  - **Analytically**, by using existing standard formulas or by deriving the relevant formulas.
  - **Numerically** by performing a Design of Experiments (Taguchi et al 1987),. These methods are often mentioned in Robust Design literature and are also used in industry (Gremyr et al 2003)
  - **Monte Carlo Simulations.** In the Monte Carlo simulation (Kumar et al 2008) input parameters are defined along with their expected variation after which a high number of iterations are calculated to finally provide a distribution curve of the resulting performance.
  - **Design of Experiments (DOE) –** using experiments on physical samples or simulations with a systematic variation

- **P-diagrams, Quality Function Deployment, Fishbone Diagrams**
  The process of identifying and visualising the design parameters that influence a given function can be supported by the use of *P-diagrams (Hasenkamp et al 2007), Quality Function Deployment (Revelle 2002), a*nd *Fishbone diagrams* (Hasenkamp et al 2007) (sometimes referred to as Ishikawa-diagrams). The identification of design parameters is essential for setting up a sensitivity analysis.

- **Process Capability Databases (PCDB)**
  Having established a sensitivity model for the design, predictions or simulations regarding the functional performance can be made, if information regarding the expected manufacturing variability can be found. For this purpose, some companies develop *Process Capability Databases* which contain data on the expected precision as a function of the production method, type of feature, material etc. Attempts at setting up and using PCDBs have often proved challenging, due to lack of communication between the manufacturing and design departments (Tata et al 1999). PCDB's are relevant to this research because predictions regarding functional performance should be

based on long-term, full-scale production capability instead of measurements from the prototyping phase, where the full extent of the potential variation is not yet experienced.

3.5 Discussion and Conclusion on Theoretical Basis

The most relevant theories, frameworks and methods concerned with Robust Design have been presented. There is a general agreement that reducing the variation in functional performance is an important aspect in terms of improving product quality. Different classifications of Robust Design methods have been presented, based on e.g. the domain to which they belong (VMF) or whether they are practices or tools (RDM). Furthermore, process approaches have been presented, that structure the methods into an ordered sequence, such as identification of key performance characteristics, assessment and prioritisation of risks, and optimisation and mitigation (VRM & DfSS).

It is argued, that the Quality Loss Function provides a meaningful and fundamental understanding of the overall mission of quality engineering – constant and nominal functional performance despite variations in the incoming design parameters – and the Transfer Function provides the same regarding the distinction between reducing incoming design variance and reducing design sensitivity. However, the QLF and Transfer Function are not ideal for application in a typical product development scenario, where a product does not only comprise a single function and the conceptual solution is not given. Typical products can have a variety of functions and subfunctions each controlled by a vast amount of design parameters.

Ideally, the design engineer would be able to design inherently robust products, quantify the robustness of the suggested solutions, and select the best solution based on a trade-off with other design requirements. The development of methods and tools with a specific support for industrial application enabling consideration to multiple functions and solutions and limited time and resources would fill a gap in the research field and enhance the adaptation of Robust Design in industry.

4. Results

In this section, the results from the research are presented. The section is structured around the seven studies presented in the DRM-model in Figure 4. The results from studies 1 and 3-7 are described in detail in Papers A-E and are therefore primarily summarised here. The results of Study 2 have not been published elsewhere and are therefore described in more detail here.

4.1 Research Clarification (*Study 1 - Robust Design Impact Model)*

Paper E - A Robust Design Applicability Model

The starting point for the research clarification is the assumption that companies are struggling with developing new products with a consistent performance. From a research point of view, it is relevant to first of all clarify, to which extent there actually is a problem worth researching, and hence make it probable, that Robust Design could play a role in improving the situation.

Despite having access to many cases from consulting projects, performance data related to the project execution (e.g. number of delayed projects) was not available. Product development has always had a shortage of performance metrics, compared to e.g. production (Buchheim 2000) where tracking and evaluating performance continually is an integral part of the activities, so it was not expected that e.g. a survey of Danish industry would be able to supply the research with data. An initial literature study on the motivations and effects of applying robust design was abundant with case examples but did not provide hard data on how robust design had affected the performance of a company on a higher level, e.g. in terms of their ability to execute product development projects. A review of 11 case companies from consultancy projects did however provide a list of motivations for applying robust design, i.e. which factors had driven the given companies to work with Robust Design (Figure 15).

ID	Organisation	Situation	Main Impact Factors	Actions	Effects
1	Medical devices	Unpredictable /delayed milestones challenged organisational planning and execution.	Minimise organisational 'noise' from **delayed project milestones.**	Integrated Robust Design Metrics into stage-gate model.	Reduced number of milestone delays. More data-driven decisions.
2	Automotive #1	*Uptime* is crucial for users. Market failures requiring service damages brand value.	Reduced **in-use failure** rate.	Implementation of a series of robust design practices and methods.	More data-driven decisions.
3	Aerospace	Design changes require lengthy re-certification.	Reduced no. of **late stage design changes.**	RDM introduced with 40+ tools & methods.	Reduction in no. of late stage design changes.
4	Defence	Tied up resources in inspection and quality control.	**Reduced lead time** and more predictable project launch and execution	SixSigma activities moved upstream to PD. DfSS-inspired activities and collaborative knowledge sharing.	Insight in internal capabilities. Tolerancing definition based on insight.
5	Hearing aids	Undefined review process. Lack of design methodology and principles.	**Reduced warranty & service costs, shorter lead times**	RDM introduced and integrated into stage-gate process.	To be defined
6	Wind turbine	Uptime is crucial for users. Cost of energy increases due to downtime during failures and repairs.	**Reduced in-use failure rate, longer service intervals,** reduced weight.	Kinematic design of drive train. Variation thinking[1] introduced for lifetime and structural analyses.	Improved lifetime of bearings. Patented concepts for suspensions and couplings.
7	Consumer electronics	Delayed launch dates. Many late stage design changes. Challenging to evaluate reliability of designs from suppliers and low-cost development site.	**Launch date predictability. Reduced no. of late-stage design changes.**	Certain RDM's and metrics introduced as part of stage-gate process.	Variation focus. Formalised review and verification of externally designed products.
8	Medical equipment for hospitals	High service expenses on equipment. Downtime is critical.	**Reduce service costs** (market failures).	Certain RDM's and metrics introduced as part of stage-gate process.	To be defined.
9	Automotive #2	Challenging to evaluate and verify reliability of suppliers' designs. Costly test programs.	**Reduce costs of testing. Reduce warranty costs.**	Robustness metrics used to evaluate suppliers' designs.	To be defined.
10	Prof. lighting equipment	Long lead time.	Cost reduction, **shorter lead time.**	Training, but no formal RDM process or toolbox.	More data-driven decisions. Less trial and error in R&D.
11	Precision scanners	Blurred images. Variation in functional performance.	Cost reduction. **Reduce functional performance variation.**	Training, but no formal RDM process or toolbox.	Data-driven decisions. Less trial and error in R&D.

Figure 15 Examples of industrial robust design projects.

The core objective of Robust Design, based on the definition of the term, is to obtain designs with functional performance that is insensitive to variation in its design parameters. However, having a robust design as such, is not interesting, especially if it is not clear if and how the sensitive design impacts the organisation. From the organisation's point of view, the main driver will always be the profit of the organisation and it is interesting to see the chain of impacts from 'design sensitivity' to 'company profit'.. The factors linking 'sensitivity of the design' to the 'profit of the organisation' were identified to form an Impact Model such as described in Blessing and Chakrabarti (2009). The Impact Model was refined during the research and the improved model is shown in Figure 16. It is possible in the Impact Model to follow the chain of impacts from the sensitivity of design parameters to the profit of the organization.

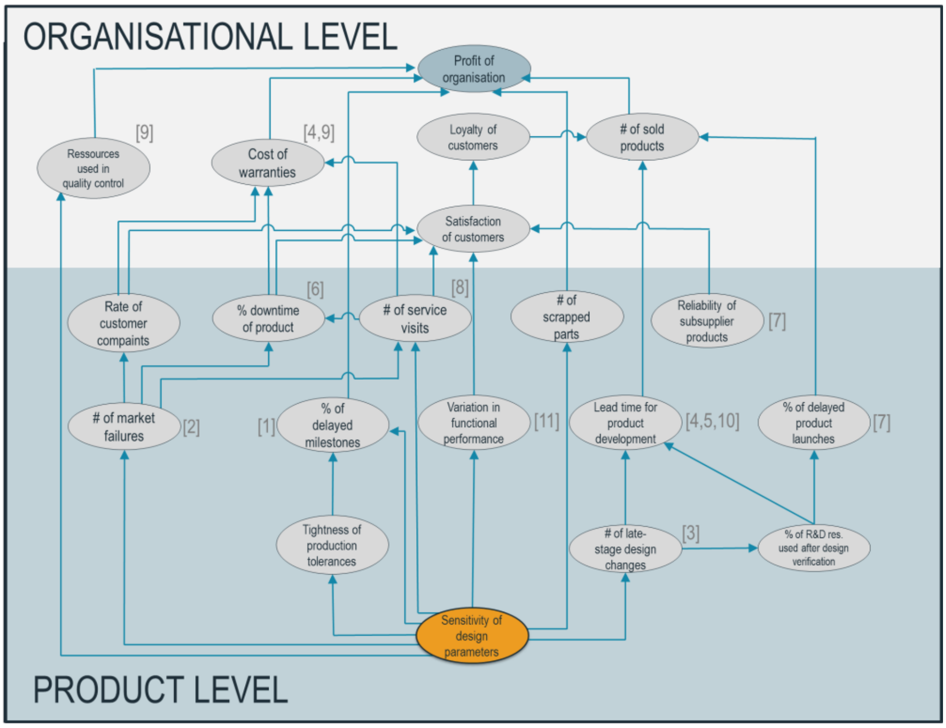


Figure 16 The Impact Model shows the causal chain from 'sensitivity of design parameters' to the 'profit of the organisation'.

This Impact Model was used numerous times throughout the research. It was the basis of the measurable success criteria in study 2a (section 4.2) and the follow-up descriptive study after robustness implementation, study 2b (section 4.8). The Impact Model has also been developed further into a prescriptive tool – *the applicability model*, where companies are able to gauge in what way and to what extent robust design is applicable in their organisation (section 4.7).

4.2 Descriptive Study 1 (Study 2a - *Analysis of Change Notes and use of R&D resources)*

Paper H – Robust Design Impact Metrics: Measuring the effect of implanting and using Robust Design

As discussed in the methodology section, it was the intention to compare historical performance data with those of future projects. Blessing and Chakrabarti suggest using the Impact Model to identify not just the ultimate success criterion (which will typically always be the profit of the company) but rather the research success criterion, which will be used to evaluate the success of the research. In order to partially verify the impact model and to prove the link between the symptoms of non-robustness and the causes, two of the symptoms were chosen for deeper investigation within a case company. These symptoms were selected as they formed part of a causal chain, but also because there were attainable data in order to measure the extent of the symptom. The chosen symptoms were:

1. **Late stage design changes**. Measure: number of engineering change notes.

2. **Misapplication of R&D resources**. Measure: R&D hours accounted for post design freeze, in comparison to pre design freeze.

4.2.1 Analysis of Engineering Change Notes

Eight recent projects were selected and engineering change notes were extracted from the company's Product Data Management-system. Engineering change notes are used by the company to track and monitor design changes. A total of 800 change notes were analysed and classified as being either a software, hardware or mechanical change. The classification was performed by a group consisting of two quality managers, a technology manager and me and was based on the descriptions of the change on the notes.

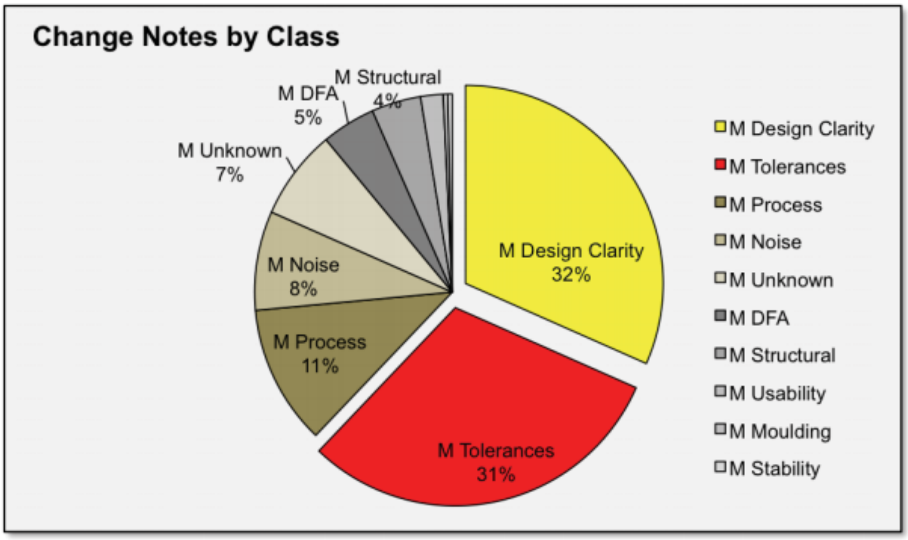


Figure 17. The distribution of 520 mechanical Change Notes from eight historical projects at a consumer electronics company

The result showed that 65% of the design changes were related to mechanical issues. A further classification was done where the 520 mechanical change notes were classified in terms of the design issue (Figure 17). The distribution showed that **63% of the design changes were related to either misjudged process capabilities (Tolerances) or so-called Design Clarity issues,** which includes issues such as conflicting parts, jamming parts, parts not interfacing on the intended mating surfaces. Incomparison, only 4% of the change notes were related to structural issues (strength of components).

These results show that the symptom of late stage design changes has a direct link to robustness related issues. While this study would need to be conducted at multiple companies in order to say anything generalisable about the importance or robust deign, the impact is clear within this case company. This methodology of analysing change notes can also be seen as a contribution of this research and can be replicated in future studies.

4.2.2 Analysis of Misplaced R&D Resources

A further study was performed to assess the usage of R&D resources. Time registrations for R&D-employees were used together with project milestone dates, to identify when in the development process R&D resources were being used. Especially the milestone 'Design Verification' was of importance, as this was the point at which the case company wished to *freeze* the design, and initiate production ramp-up. Ideally the share of R&D man-hours after Design Verification should be lower than 15% (according to a quality manager from the company), since the product should be ready for production ramp-up and design changes should be kept to a minimum after this point. The results of the study are shown in Figure 18. It is seen that all four projects used significantly more than 15% of the total R&D resources after Design Verification. Three of the projects actually used more R&D resources *after* the design verification than before. ***Over the four projects, 230% more R&D resources were used after design freeze than before***. The problem with the current situation therefore lies in the lack of predictability of the project execution, resulting in milestone and launch delays, as well as the risk of launching products with design issues yet to be discovered. Furthermore, it is often the case that experienced R&D resources are pushed forward to firefight the post design-freeze issues and as a result, the new projects are under resourced in terms of experienced engineers.

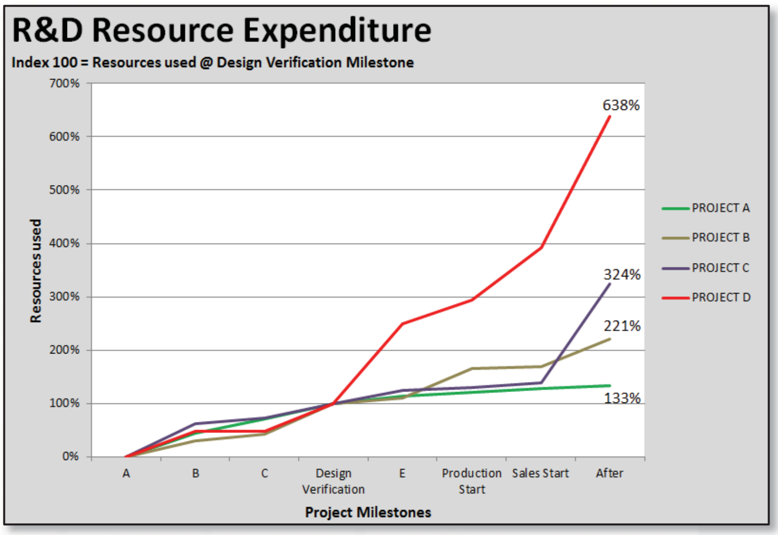


Figure 18. R&D Resource Expenditure in a consumer electronics company. Three out of four projects used more R&D resources *after* Design Verification than before. The data is indexed such that the R&D resources used at the Design Verification milestone is defined as index 100.

The late-stage use of R&D resources indicates that certain issues are not discovered by the company's testing and design review procedures. The issues are identified late in the development process, despite testing and reviews. There are many potential reasons for this, one being the increase in parameter variation which is experienced, when a design moves from low volume, single cavity, single batch prototype production, to high volume, multiple cavity, serial batch production. Having unrobust and coupled designs (see Axiomatic Design in Section 3.2.4) may also lead to a Rubic's cube or quality-whack-a-mole[1] situation where fixing rampup issues can take an eternity of parameter tweaking.

[1] Anna Thornton (2015) "Stop playing quality-whack-a-mole" Linkedin Post - https://www.linkedin.com/pulse/stop-playing-quality-whack-a-mole-anna-thornton

Discussion and Conclusions from Research Clarification:
Although data from only one company was analysed, the results strengthened the assumption that companies especially struggle with issues during the production ramp-up and that despite testing and product reviews prior to the design verification, a substantial number of design changes and design resources are still required before the product is ready for launch. The data created a baseline for measuring the effects of proposed solutions.

The development of the Impact Model also raises a general discussion point triggered by a comment from a reliability and robustness specialist, who said: "Management does not prioritise robustness activities". A possible explanation for this could be the lack of a transparent link between design sensitivity and company profit. In production, where metrics are more common, cost of scrap and yield-performance have been main drivers for the introduction of LEAN and Six Sigma-programs. With the development of the impact model and the partial validation of two of the symptoms, it is hoped that R&D managers will see more clearly the causal links between non-robustness and the company's bottom line.

4.3 Descriptive Study 1 (Study 3)

Paper A – A Classification of the Industrial Relevance of Robust Design Methods

The purpose of this study was to evaluate to which extent existing Robust Design methods meet the needs of industry. The study presents a set of success criteria that can support the successful adoption of Robust Design methods in industry:

1. **Leading indicators of large functional variation.** To enable the possibility of any corrective action by the design engineer, data must be available while the design phase is still ongoing. In a development environment, the design properties (structure, form, dimensions, material, and surface quality) will be modified regularly and therefore either analyses with short loop-backs or analyses that provide leading indicators are preferred, such that the results are not outdated by the time they reach the design engineer. An example of this is using Design of Experiments to provide specific data on the functional performance of the product, which could take several days, compared to simply counting the number of parameters influencing a given performance, which is a quick way of getting a leading indication of the performance variation.
2. **Quantifiable metrics.** There is a tendency in industry that management wants to make data-driven decisions. Therefore, there is a need for quantifiable metrics that allow for comparison with alternative solutions, previous projects, industrial standards or competitor products. This criteria is also stated by Thornton (2004).
3. **Early-stage application**. The cost of design changes increases exponentially as a development project progresses. Metrics and methods that are applicable at an early-stage are therefore preferable. More specifically, a distinction is made between the level of information needed to apply a given method,

where information could refer to sketches, dimensions, tolerances, physical models, product structure, etc. The less information that is required, the earlier the method can be applied.

The study finds that there is a gap between the existing Robust Design methods and the needs of industry. The classification shows that Robust Design Principles and Kinematic Design / Design Clarity are categorised as early-stage methods, but their presence in Robust Design literature is limited and not even mentioned in the surveys regarding the use of specific RD methods (Gremyr et al 2003). The FMEA can be applied continuously and iteratively during the design project as more and more information about the design becomes available, but the results depend on the experience and competencies of the FMEA-team and the results are not quantifiable in a way where a project can be compared to e.g. historical project performance. Finally, DOE and Taguchi methods are classified as belonging to the late stages of the design process, as physical prototypes, detailed design information and process capability data are required to apply these methods.

It is suggested that the Robust Design Principles and Kinematic Design should be given more focus as Robust Design Methods because they fulfil the industrial success criteria and could contain an untapped potential in terms of improving the robustness of designs at an early stage.

Discussion and Conclusions from Descriptive Study 1 (Study 3):
The study extends the conclusions from previous studies (Gremyr et al 2003; Andersson 1996; Matthiassen 1997; Thornton 2000) stating that Robust Design methods are complex to use and only applicable late in the development process, by categorising commonly used Robust Design methods in terms of the applicability in industry. It is vital to understand the nature of the design engineer's way of working, having to fulfil multiple requirements involving trade-offs and many iterative design loops resulting in a constantly changing design, which especially in the early phases of the development process, does not allow for methods and tools which have long lead-times.

It is concluded that the existing suite of Robust Design methods could be improved in terms of the industrial applicability, especially by being applicable in the early design phases (fast iteration loops), being quantifiable and objective.

4.4 Prescriptive Study 1 (Study 4)

Paper B – The Foundation for Robust Design: Enabling Robustness through Kinematic Design and Design Clarity

This study first argues that adhering to the principles of Kinematic Design, Minimum Constraint Design and Location Schemes is closely related to the variation in Functional Performance of the design. As stated in section 3.4, these are existing principles, but they are primarily used for mechanism design, robotics and precision engineering, i.e. in products with strict demands on performance variation. However, the principles can also be applied to static products produced in high-volumes, The underpinning argument is that by eliminating unnecessary constraints, the *information content* of the design is reduced (Axiom 2 of Axiomatic Design). Already at the conceptual level, it is possible to use *Kinematic Mobility* as a driver for defining how the bodies of the product should interact and it is possible to define an intended set of constraints, which describes how all bodies and parts of the product should interface with eachother. Although Mobility is typically used for moving mechanisms, the principles are equally applicable for static designs and they secure clear and consistent force transmission paths and tolerance chains, allowing for an early assessment of structural and tolerance aspects.

During the detailed design phase, the engineer is supported by a suggested set of specific design guidelines (Figure 19) that increase the predictability and reduce the variation in Functional Performance. The principles are founded on the underlying theory of minimal constraint design and are directed at detailed generic design scenarios, where experience has shown that unwanted constraints are observed in the design.

Both the system and detailed design principles are supplemented by simple metrics for quantifying the level of predictability based on the number of overconstraints on both the system and detailed design levels. The resulting number, the Predictability Index® (invented and trademarked by Valcon), is a leading indicator for the robustness of the design.

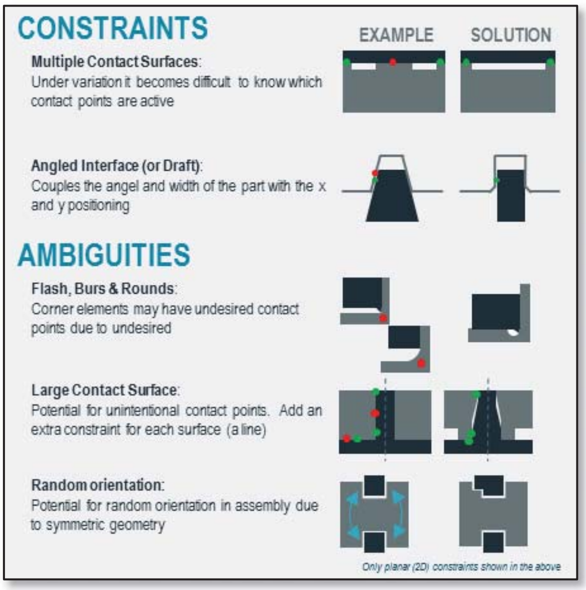


Figure 19. Definition of constraints and ambiguities (refined version of Table 2 in Paper B)

Since the introduction of the Predictability Index®, more than 50 products from various industrial sectors have been analysed and compared with their performance. Where possible, the resulting indices are compared to the known performance of the product during ramp-up and product launch and on this basis, a rough scale (Figure 20) has been developed that can be used to place the product on an absolute scale in terms of the level of issues that should be expected during ramp-up. The scale is indexed based on the number of interfaces in the product, thereby making it possible to compare e.g. a car with many interfaces to a medical device, with much fewer interfaces.

Predictability Index	Predictability Scale	Expected effort requirement during Product Introduction (Ramp-up)
0	**Optimal** – no issues left	Minimum effort. No surprises
0 - 3	**World class** - very few issues left	Large effort on a few dominating issues
3 - 5	**Above average** - few issues left	Large effort on several but repeatable issues
5 - 15	**Average** – a large number of issues left	Very large effort on many and changing issues
15 - xx	**Below average** – a very large number of issues left	Very large issue driven effort on continuously changing issues

Figure 20. The Predictability Index scale can be used as a leading indicator for expected variation in Functional Performance

The Predictability Index® and the underlying principles of Kinematic Design have been applied in Robust Design training programs run in industry and academia (Figure 21) as well as for design reviews in Valcon and the definitions and notations of constraints, over-constraints, and ambiguities have been refined since the publication of Paper B, based on these experiences. The Predictability Index® has proven valuable for e.g. supplier selection, where the designs from potential suppliers were *scored*, and for evaluating the quality of designs made by the companies' off-shored design departments in low-cost countries. Promising attempts have also been made using Kinematic Design as a synthesis tool. Because there are only 6 Degrees of Freedom (6DOF) between two components, there is only a finite number of kinematically different ways of creating e.g. a four-bar linkage. In this way, Kinematic Design is used to define the intended constraints between all components of the design prior to sketching any solutions and thereby supports a *right-first-time* approach, where designs are inherently robust, as opposed to first sketching, then analysing and finally optimising the design.

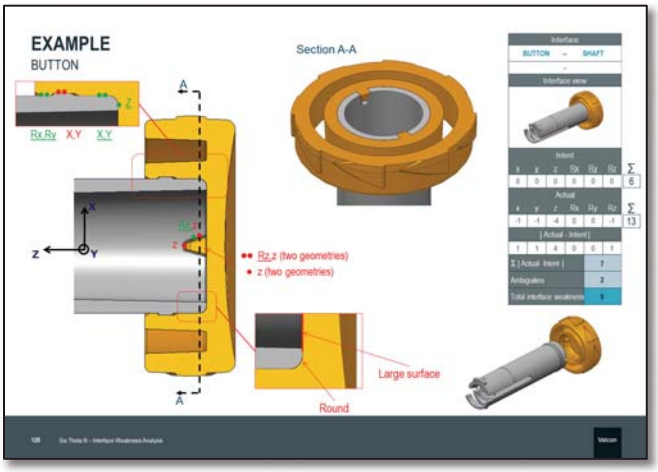


Figure 21. An example slide from the Robust Design training. Each interface in the design is systematically reviewed to find and remove overconstraints and design ambiguities

Adhering to the principles of Kinematic Design is seen as the foundation of Robust Design. If a product is not predictable, any subsequent testing, simulation or analysis does not give an accurate picture of the performance of the product and is therefore of limited value. As a simple example, Figure 22 shows two different café tables with three and four legs respectively. The design with three legs is said to be ideally constrained whereas the one with four legs is overconstrained. Simulating the stress levels in the legs is straightforward for the three-legged table as the force is (close to) evenly distributed on the three legs. Simulation the stress levels in the four-legged table would require that assumptions to be made regarding the flatness of the pavement, the length and angles of the legs, etc. Best case, calculating the Functional Performance (the stress in the legs) would be more tedious; worst case, the assumptions are wrong and the results are not valid. Therefore, it is fundamental that predictability is achieved prior to any subsequent robustness analyses.

Figure 22. A table with three legs vs. a table with four legs. If a force is applied to the table, the transmission of forces should ideally be predictable, despite variation in the design parameters. The three-legged table is more predictable than the four-legged table.

It has been argued that the majority of the Robust Design tools are analytical by nature. From a practical point of view, it can be valuable to further distinguish between the types of analysis tools. Some tools require substantial resources and have long lead times and are therefore primarily used at design reviews and project milestones. Other tools only require limited resources and have short lead-times (maybe even realtime) and can therefore be used at any given time in the development process. In paper C, it is claimed that the proposed design principles are *applicable at the point-of-design*. This is a pragmatic way of describing that the tool can be applied i) by the design engineer alone, and ii) integrated in to the process of sketching alternative design solutions. Because of its simple nature, it is claimed that the analysis behind the Predictability Index® is applicable at the point of design whereas a DOE or an FMEA do not fulfil these criteria, because they are specialist driven and are not used as an integral part of the sketching and solution generation process. Especially during the early stages of the design process, where changes to the design occur frequently, tools that are applicable at the point-of-design are preferable.

Discussion and Conclusions from Prescriptive Study 1 (Study 4):
The principles of Kinematic Design and Exact Constraint Design are not new. However, expanding the principles from mainly being applied to mechanisms and precision engineering products to being applied on generic products is new. Furthermore, using the number of overconstraints and design ambiguities in a product as a simple and fast leading indicator has proven to be useful in industrial projects. Having unique and clear interfaces throughout the product has had positive implications for the tolerance and structural analysis work, as the tolerance chains are now more well-defined and easy to derive and the load transmission paths (a path indicating how an incoming load e.g. from a user of the product propagates through the different parts) are also more clear.

4.5 Prescriptive Study 1 (Study 5)

Paper C – Robust Design Principles for Reducing Variation in Functional Performance

This study presents an extended and higher-level view on Robust Design Principles, compared to the Kinematic Design principles. Obtaining predictability, as described in the previous section, supports the repeatable behaviour of the product, but efforts can be made to reduce the variation in Functional Performance even further. The objective of the study has been to use the design engineer's everyday practice as a starting point and define possible ways of reducing functional variance.

A catalogue with 15 principles is presented along with case examples of how they can be applied and the pros and cons of using them. By suggesting design principles, further *design support* is given to the design engineer. The catalogue can be used proactively as inspiration for reduction in performance variation, as well as reactively, if it is found that the Functional Variation leads to an unacceptable quality loss or if design specifications are not being met. The intention of the catalogue has also been to widen the solution space in terms of variation reduction and avoid the tendency to demand tighter and tighter tolerances from production, which is a very commonly used principle for keeping functional variation within a specified limit.

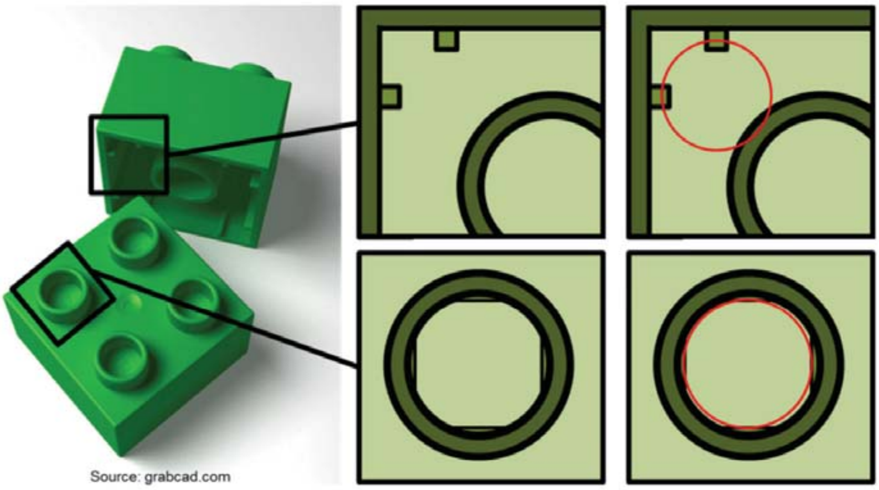


Figure 23. Example from 'Design Principle no. 6: Flexibility'. By designing distinct and small deformation zones, the variation in *clutch force* of LEGO®-bricks can be reduced.

Discussion and Conclusions from Prescriptive Study 1 (Study 5):
The suggested design principles are an extension of the principles of Kinematic Design and Design Clarity. A design engineer will face situations, where it is not possible to obtain a design that is ideally constrained or a situation where – for some reason – the variation in functional performance exceeds the target specification. The study presents a catalogue of design strategies all aimed at reducing the variation in functional performance. The catalogue is intended to serve as inspiration for the design engineer.

4.6 Prescriptive Study 1 (Study 6)

Paper D – How to Implement and Apply Robust Design: Insights from Industrial Practice

The lack of uptake of robust design cannot only be related to the complexity of the methods and lack of applicability in early-stage design. Organisational change management is also key to any successful implementation. The purpose of study 4 was to identify successful ways of implementing and applying Robust Design in industry. Four companies that were known to have successfully implemented robust design were selected. To gather a wide array of experiences, the companies were chosen from different countries and from different industries, but had in common that they develop and produce mechanical and electromechanical designs. The companies were interviewed to identify why they had implementd robust design, how they did it, challenges along the way, factors leading to the successful implementation and experienced effects.

The analysis of the results, which are summarised in Figure 24, showed that there is no one way of implementing and applying robust design, as each company had a different approach, which fit to their company culture and the type of products they were developing. As a result different implementation archetypes were created to inspire R&D managers to choose and take inspiration for the archetype that they think best fits to their company.

Detailed descriptions of the implementation in two of the interviewed companies can be found in Mashhadi et al (2012) and Parsley et al (2013).

	MED	DEF	AERO	AUTO
Why	Delays in late design stages Shorter and more predictable lead-time	Internal cost of poor quality Resources tied up in control and inspection	*Cost of non-quality* Expensive 'in service' changes Cost of redesign due to validation procedures	*Cost of non-quality* Avoid failures in market Maintain brand reputation
How	Defined roles and responsibilities Robustness Cockpit with six KPIs and requirements	Gradual implementation of Six Sigma and DFSS-practices Defined System Engineer role	Training of engineers + chief design engineers Certification scheme with robustness	Toolbox of 15+ RD tools Training and coaching (after failed attempt using external trainers)
Challenges	Resistance to change RD seen as an add-on to existing development activities	Lacking adoption of RD-tools and methods Visualising the usefulness of DoE after to initial unsuccessful use	Different perception of the novelty in the initiative The initial process towards RD was over-formalised	Unsuccessful 'tool-pushing' by external consultants No acknowledgement of need for change
Success factor	Personal qualities and competencies of chief/lead engineers Coaching and support of lead engineers	Gradual implementation of Six Sigma practice Consistency in definitions of framework	Training and courses focus on chief design engineers Having tools that are used on daily basis	Engagement and training of middle management Transition from external 'tool-pushers' to internally driven processes
Effects	Guidance on how to develop good designs Increased transparency for management	Cross-functional collaboration Design reviews increased insight in design features	More insight into their own design & understanding of the product behaviour Saved time in product development process	Stronger focus on knowledge and facts Increased understanding of the root causes of failures

Figure 24. Overview of main findings from interviews in companies applying Robust Design

Discussion and Conclusions from Prescriptive Study 1 (Study 6):

Change in individual and organisational behavior is often resisted. A prerequisite for RDM becoming more widely used in industry is that people must do things in a different way to what they are doing today. How to successfully drive a change in an organisation is a comprehensive discipline dealt with in the field of Organisational Change Management. These aspects are seen as generic, i.e. irrespective of whether the subject of change is robust design, LEAN R&D, or Agile Product Development, and involve aspects such as management attention, communication, training, incentives etc. Of course, these aspects also apply to a Robust Design initiative, but because they are treated in greater detail elsewhere, they have not been included in this research. However, specific aspects of implementation and use of Robust Design in industry have been researched by interviewing four front-runners within the use of RD.

All of the front-runners have invested substantially in training, updated development manuals, consultants, tool development, and definition of new roles and responsibilities to implement robust design. In that respect, the implementation can be compared to the implementation of e.g. LEAN, which also requires an investment to become a success. The definition and application of Robust Design is performed in different ways in the four companies. This can partly be explained by the context in which the companies operate, including requirements from regulatory authorities or from clients. For example, in the automotive industry, it is often required that subsuppliers deliver an FMEA together with the component or product being delivered. The ways of applying robust design is described as four archetypes: Metrics based, Collaborative, Formalised and Integrated. The archetypes are intended to serve as inspiration and guidance for companies considering implementation of Robust Design in their organisation.

The main conclusion from this study is that Robust Design can be applied in different ways depending on the context, the company culture, the aim of applying it, etc. The presented archetypes are not exhaustive, but serve as inspiration as to how companies considering to use Robust Design can implement and drive initiative. It is interesting that only the AERO-company uses what could be called the classic version of Robust Design, where the actual design sensitivity is calculated (using DOE's), whereas the other three companies use alternative approaches involving e.g. kinematic design, FMEA's, design reviews and focus more on the 'awareness of variation' than full-scale analyses of how variation affects the performance of the product.

4.7 Prescriptive Study 1 (Study 7)

Paper E – A Robust Design Applicability Model

The starting point for this study was a series of observations from working with Robust Design in industry and as a researcher. There was a wide variety of motivations for wanting to apply Robust Design amongst the clients in Valcon as well as the cases from literature. Furthermore, robust design was presented in literature as a generic *one-size-fits-all* methodology, but it had become more apparent over time, that companies were at quite different maturity levels in terms of having a well-defined product development process, expressed reliability requirements, failure tracking etc. Furthermore, there was often not a common understanding within the company about the current issues as well as the success criteria for the Robust Design initiative. To address these issues, a study was proposed for deriving and defining a maturity and applicability model for Robust Design.

The presented Applicability Model assesses the relevance of Robust Design to the organisation by use of a simple self-assessment, in which relevant employees in the company are asked to score the importance and performance of 13 different factors, known to be related to robust design. If the company experiences factors with high impact and high occurrence, there is an increased probability that robust design will be applicable in the company. The model is deliberately kept very simple, as it is only intended for use as an initial assessment.

The Applicability Model has been tested on a group of reliability and quality managers and has also been made accessible as an online self-assessment (which can be found at http://www.robustdesign.org/survey). The model was well accepted as a means for establishing a common understanding of the important drivers to the company and as a basis for digging deeper into specific performance metrics that could act as drivers for subsequent quality engineering and robustness initiatives. On a side-note, it was interesting to observe how employees from the same company scored the company quite differently, which could indicate a lack of common understanding of the company's quality related success criteria and current performance.

ID	Factor	1 - Low impact	5 - High impact
1	Launch date precision	Launch dates have minor influence on profitability, e.g. due to long market life, lack of competitors, lack of technological edge	Launch dates highly influence profitability e.g. due to seasonal sales, a small market lifetime, or products being part of a larger engineering system (e.g. automotive).
2	Milestone precision	Minor importance, e.g. single-project or small organisations.	Delayed milestones cause major disruptions in the organisation planning e.g. in large organisations or organisations with large development portfolios. Key resources become tied up, affecting other projects.
3	Late-stage design changes	Low importance, e.g. due to in-house production, production-on-demand, simple or no tooling.	High importance, due to e.g. costly production tools (e.g. moulds), large inventories, long production lead times, complex supply chains
4	Customer complaint rate	Customer complaints have a minor impact due to e.g. easy complaint handling or low cost of replacement and service	Customer complaints have a high impact due to e.g. costly complaint handling, high brand expectations, or high replacement costs.
5	Development lead-time	Minor importance, e.g. if R&D costs constitute a minor share of overall product cost, markets with slow technological development.	Major importance e.g. due to R&D constituting a substantial share of overall costs, fast moving technological development in the market, fast moving market needs & expectations
6	Scrap rate	Scrap rates have little or no effect on the profitability of the organisation.	Scrap rates strongly affect the profitability of the company, e.g. due to high component costs or small profit margins.
7	In-market failure rate	Minor importance due to e.g. disposable single-use products, low-cost products, low customer expectations.	High importance, due to loss to brand value, cost of recalls, cost of replacement, safety aspects.
8	Variation in functional performance	Minor consequences of variation in performance, e.g. low-cost products.	High precision demands (e.g. measuring equipment, high-end products and medical devices).
9	Downtime of product	Uptime has little importance, e.g. for low-cost and disposable, single-use products.	Uptime extremely important due to e.g. quality agreements, safety issues (e.g. wind turbines and airplane engines).
10	Reliability of products/components from sub-suppliers	Minor impact, e.g. due to liability agreements, outsourcing of non-critical components or lack of outsourcing	Major impact due to e.g. outsourcing of complete product development project, liability agreements, or outsourcing of critical components
11	Tightness of production tolerances	Minor impact, e.g. due relatively low cost of components, low production volumes, or ease of adjustment during production	High impact, due to e.g. high production volumes, tooling with no adjustment options, or expensive components.
12	Service visits	Service visits have minor impact due to e.g. short distance to customers, low production volumes, high serviceability, disposable/single-use products, and mandatory service schedules	Service visits have major impact due to customer expectations, long distance to customers, complex serviceability, high production volumes, and long market life
13	R&D resources used after design verification	Minor impact due to uniformly skilled engineers, simple resource re-allocation, high profit margins, and flexible supply chain.	Major impact due to senior engineers being needed for conceptual work on other projects and sensitivity to budget overruns.

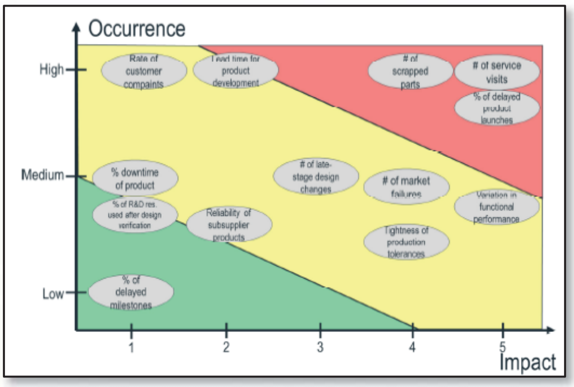


Figure 25. The Applicability Model is based on an evaluation of the assigned importance and the observed performance on impact factors related to the robustness of a product (left). The result is presented in a matrix-structure with the high-impact, high occurrence factors placed in the top right corner (right).

Discussion and Conclusions from Prescriptive Study 1 (Study 7):

The Applicability Model is presented as a tool for measuring the relevance of Robust Design based on the occurrence and importance of factors that are related to Robust Design. The Applicability Model should primarily be seen as a scoping and alignment tool to be used to support decisions on whether to apply Robust Design and for identifying and communicating which key factors that the initiative should improve, e.g. the number of delayed milestones or the tightness of tolerances.

4.8 Descriptive Study 2 (Study 2b)

This study is a follow-up on Study 2a. and the Prescriptive Study. The original intent of the study was to introduce selected foundational robust design methods, tools and principles (proposes in paper B) to design teams starting up new development projects in the case company, and then compare the performance of these projects with the baseline created in Study 2a. In the first project, the principles were introduced to the design team, but the analyses were conducted by me at relevant design iterations, along with suggested design changes. The Predictability Index® was used to track the progression of the design. In the two subsequent projects, training was given to the engineering design teams. However, one project was moved to an external development department, which prevented access to the R&D time registrations and in the second project, the milestone dates were changed and compressed to an extent that made the data unreliable. Therefore, only one data set exists, which is shown in Figure 26.

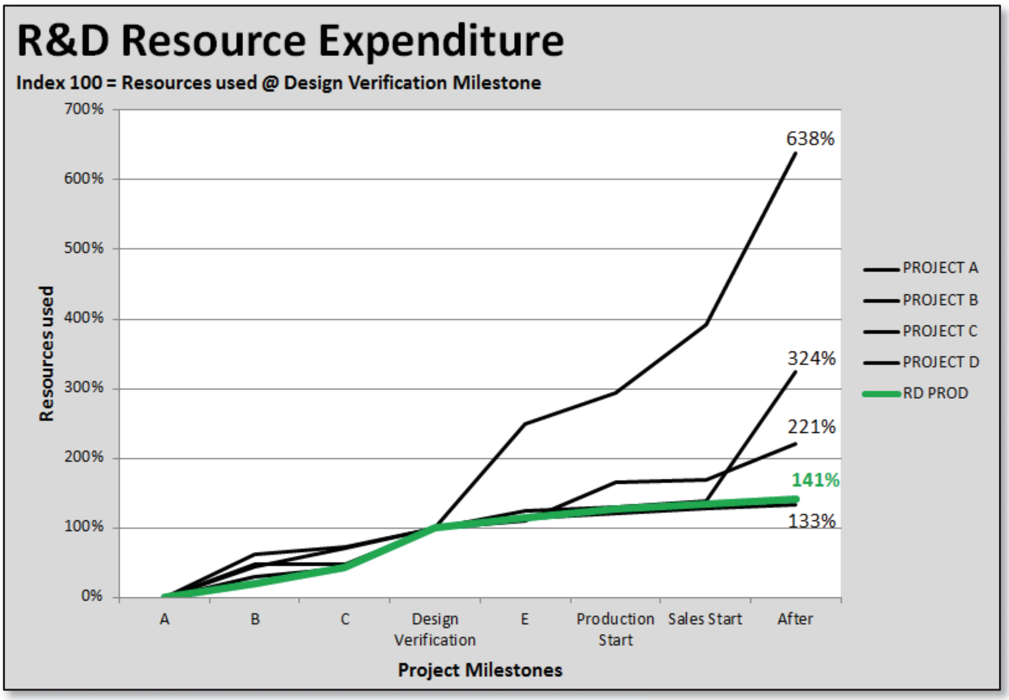


Figure 26. Follow-up study evaluating the effects of using Robust Design

The figure shows the four historical projects (black lines) in combination with the RD-project using the Predictability Index® and the underlying design principles. The performance of the RD-project indicates that there could be a positive effect of applying RD principles, but with only one data set, this could also just be a 'lucky punch' and therefore no solid conclusions could be made. However, the general feedback from the design engineers was positive and as the project manager expressed it, the Kinematic Design tools "give a very good overview of construction maturity and for tracking the development progress." The Predictability Index® (and the underlying Kinematic Analysis) is now part of the required deliverables at milestone meetings in the case company.

Apart from the case study, Kinematic Design has become a very integrated part of the everyday design workflow at Valcon and it has also been fully installed in the large medical device company mentioned in section 4, where the Predictability Index® has also become a mandatory part of the requirements for passing a project milestone.

5. Conclusion

Product quality is recognised as a decisive competitive parameter for production companies. The ability to develop and produce products with a performance that consistently meets user expectations is becoming ever more important in a globalised market. The direct and indirect costs resulting from quality issues either during development or in the market can significantly affect the profit of the company. This research project was motivated by the continuous challenges faced by industry during the development of new mechanical products, including delayed product launches, quality issues during production ramp-up and unsatisfactory product performance. The research has investigated the challenges encountered by industry to identify improvement areas to the existing methodology. This section summarises the findings of the research and the core contributions as well as evaluating the research and its importance to academia and industry.

5.1 Findings

The research has been guided by the four research questions, presented in Section 1. The research questions have been addressed in seven studies, which have been described and published in the five research papers (A-E) appended to this thesis and in Section 4. The research findings are presented by going through the Research Questions one-by-one and concluding on the obtained results.

RQ1 – What is the impact of Robust Design?

The typical costs of quality (prevention, appraisal, failures, lost opportunities) constitute 10-40% of a company's revenue, so the potential benefits of successful quality improvement initiatives are obvious. Robust Design is a quality engineering methodology that specifically addresses quality issues related to variation. Issues related to variation are often first discovered late in the development process when the variation from serial production is experienced. This is also where the costs of making design changes are high, since investments have already been made in production and assembly tools, inventory, etc. In a case study of four *new product development* projects it was shown that on average the R&D overspend was 230% post design freeze. This could be attributed to issues not related to robustness, but when the change notes were analysed it was found that 65% of the mechanical design changes made in late-stage design could be attributed to robustness issues. This means, that successful implementation and use of Robust Design could potentially have a significant impact on the overall success of the company. The research found that even though Robust Design is active as a research field and that product quality is a key competitive parameter, Robust Design is relatively unknown in industry and even amongst companies that know what Robust Design is, use rates are limited. This indicates the presence of a potential that could be exploited, if Robust Design became more widely adopted by industry.

RQ2 – To which extent do current Robust Design methods meet industry needs?

The main barriers for industrial uptake of Robust Design are the complexity of the methods, particularly the highly statistical approach and the challenges of using Robust Design in the early design phases, where the conceptual design is defined. Ideally, design methods should match the everyday work of the design engineer and provide relevant support in each of the generic design stages from conceptualisation over embodiment design to detailed design. In literature, robust design is often applied as an optimisation exercise on a *single* function in a *single* concept, which has reached a detail level, where all the design parameters (structure, form, dimensions, materials, and surface quality) have been defined. In reality, the engineer typically has multiple functional requirements to fulfill, has several design suggestions for each function, and due to trade-offs and ongoing realisations made during the development process, the design is changed and adjusted in short iteration loops, often without having specified the full set of product properties. For a design tool related to robustness to *fit in* to this context, it has to be:

- Simple and fast – to keep up with the iteration speed of design changes
- Quantitative – to enable comparison of multiple solutions and support decision making
- Objective – making results comparable across the organisation and independent of personal judgments

The 'classical' definition of robust design, where the robustness of a design is quantified using Design of Experiments, Transfer Functions and Signal-to-Noise Ratios is found to only give limited support to the design engineer and require a level of statistical knowledge that the average design engineer does not possess. The more qualitative methods such as Failure Modes and Effects Analysis and Fault Tree Analysis are often used in industry, especially in the automotive, medical device and aerospace industries, and although they are updated several times during the development process, they do not provide direct support and guidance in the design situation. In other words, there is a time lag from the time a solution is sketched to the time where the quality of the solution is measured and fed back to the design engineer.

Frameworks such as Variation Risk Management and Design for Six Sigma have emerged and added structure to the quality engineering toolbox and have suggested stepwise processes for applying tools and methods related to the reliability and robustness of a design, including the identification of relevant key functional requirements (or characteristics), which has earlier been seen as part of the explanation for the lack of RD usage.

The research finds that there is a potential for providing better support to Robust Design activities in industry. It is suggested to investigate and further develop design guidelines and leading indicators for robustness to create an extension to the current suite of relatively 'heavy' analytical tools. Using leading indicators can give a leading *indicative measure* of the robustness of the product at an earlier point in the design process, where the costs of making design changes are lower.

RQ3 – Which methods, principles and metrics can address the shortcomings of current RDM?

The research found, that by combining the principles from Axiomatic Design and Kinematic Design, the number of design parameters controlling the functional performance of the product and the degree to which they are coupled could be reduced, giving a positive effect. This finding is in line with the principles from precision engineering, which have exceptionally low tolerances for variation in performance.

If a design does not adhere to the principles of Kinematic Design, the force transmission paths will be ambiguous and the tolerance chains will not be uniquely defined. In essence, the design is unpredictable and any subsequent robustness analysis would have to be based on assumptions and more importantly, the product will be prone to a larger variation in functional performance, due to the influence from additional control factors. Therefore, the principles of Kinematic Design are claimed to be the foundation for robust design. A metric called the Predictability Index® is proposed. It is a function of the number of over-constraints on system level (between mechanism bodies, even if these are static) and over-constraints and ambiguities on part level. A Predictability Scale is presented based on experiences from analysing more than 50 products. The index does not provide a direct measure of the robustness of a product, but rather a leading indicator giving an early indication of the expected level of issues related to variation. The index can be used to compare solutions or products and act as guidance for the selection of the best solution.

Attempts have been made also using Kinematic Design as a synthesis tool, by first defining the intended constraint sets (location schemes) and then sketching conceptual or detailed design solutions based on these. This process shortens the development time, by directly obtaining a kinematically correct design, rather than having to design, analyse and redesign. When a predictable and unambiguous design is obtained, traditional Robust Design activities can come into play, focusing on the reduction of design sensitivity.

It is often seen that the design engineer is challenged by narrow tolerances on variation in performance. Experience shows that this is often solved by transforming the narrow tolerances to the production drawings, but if the desired tolerances differ from the process capability, late-stage design issues will occur, when production is ramped-up and the true variance of the process is experienced. To widen the solution space and to act as inspiration for the design engineer, a catalogue of 15 robust design principles is presented. The principles show alternatives to Kinematic Design, because situations can occur, where an ideally constrainted design is not possible and this may require alternative principles to be used.

In conclusion, the research question has been answered by taking existing principle from mechanism design and precision engineering and using them as a driver for reducing the number of influencing design parameters. Furthermore the Predictability Index® has been introduced as a metric that can be used as a leading indicator for subsequent robustness issues. Finally , a catalogue of design guidelines for minimising functional variation – or fulfilling tight tolerances on performance – is presented.

However, effective methods and well-defined processes alone are not necessarily enough to ensure a successful adoption by industry. Therefore, the research also addressed the question:

RQ4 – How can Robust Design methods become more widely used in industry?

For companies to consider the implementation of any new methodology, they must first see their current performance as an issue and next identify whether there is a match between their experienced issues and the known effects of the methodology. In literature, Robust Design is often limited to the presentation of a single case, and the wider implications of having or not having sensitive products is not given much attention. The research claims that the lack of success for Robust Design can be partly attributed to not having created a clear link to the consequences on a higher scale, which makes it challenging for decision-makers to see the rationale for the adoption of new methodology. The research presents a Robust Design Applicability Model (RDAM) that comprises 13 questions to be answered by the company as a self-assessment exercise. The companies are asked to score the impact and occurrence of specific quality issues Robust Design has shown to have a positive effect upon. The RDAM is intended as a simple and quick way of assessing whether Robust Design could be of relevance to the company. RDAM can also be used to identify success factors for any subsequent initiatives as well as creating awareness in the organisation about current performance.

Furthermore, the use of Robust Design in industry has been researched by interviewing four front-runners within the use of RD. The ways of applying robust design is described as four archetypes: Metrics based, Collaborative, Formalised and Integrated. The archetypes are intended to serve as inspiration for companies considering implementing Robust Design in their organisation. The archetypes include descriptions of the methods, roles & responsibilities, success factors and effects, all of which differ between the four companies.

The proposed principles and methods have been applied in a number of industrial projects, as well as in a case study, to evaluate the effects. Results from the case study indicate a potential for a considerable reduction in late-stage design changes. Qualitative feedback from project managers and design engineers has been good and promising.

5.2 Testing of the hypothesis

The hypothesis stated that:

Hypothesis
There is a potential for increasing the industrial uptake of Robust Design methods if an implementation strategy is defined and methods applicable at the point-of-design are implemented.

The hypothesis is tested by holding it up against the research questions and the related findings.

The findings related to RQ1 (robust design impact) are not directly related to the hypothesis but can be seen as part of the implementation strategy. Findings from consulting projects show that the level of uptake in an organisation after e.g. a training initiative strongly depends on the alignment and common understanding of the issues faced by the organisation, i.e. is there a clear understanding of the need for change and have the success factors been identified.

The findings related to RQ2 (methods meeting industry needs) supports the hypothesis by concluding that the current Robust Design methods are to a large extent *not* applicable at the point-of-design and that the current uptake of Robust Design is limited. It is found from existing surveys, that the lack of uptake is linked to the complexity and lack of early-stage applicability of the methods.

The findings related to RQ3 (methods, principles and metrics) also support the hypothesis by first presenting specific methods and principles which are applicable at the point-of-design and hence implementing these in various organisations (as consulting projects).

The findings from RQ4 (how to become more widely used in industry) state that companies successfully applying Robust Design today, have had a clear implementation strategy and allocated considerable resources to e.g. training and definition of roles and responsibilities. It is also found that these companies focus more on the awareness of variation and methods such as design reviews, FMEAs and Kinematic Design, and less on DOE's and design sensitivity.

The findings provide strong support of the hypothesis as there are indications that companies applying robust design have had clear implementation strategies and apply methods and principles that are simpler and easier to use than 'classic' Robust Design tools, but further research is necessary to prove the hypothesis.

5.3 Core contribution

The core contribution of the research is the collective set of principles and guidelines on how to implement and apply Robust Design in an industrial context.

More specifically, the core contribution includes:

- The definition of a Foundation for Robustness – guidelines for designing unambiguous and predictable products using Kinematic Design principles
- Predictability Index® - an analysis method and a metric acting as a leading indicator for expected robustness issues.
- Robust Design principles for reducing performance variation – a catalogue of 15 design principles contributing to minimal variation in performance
- An impact model describing the link between from robustness to company profit.
- An applicability model measuring the relevance of Robust Design based on the occurrence and importance of specific issues related to Robust Design.
- Application archetypes – inspiration and guidance from front-runners on how to implement and apply Robust Design
- Quantifying the impact of robustness empirically though several case studies and an analysis of change notes and R&D resource allocation.

5.4 Evaluation of the research

In addition to the *measurement of* success described in the Descriptive Study 2 (Section 0) the results of the research are also evaluated in terms of their usability and applicability, as described in Blessing and Chakrabarti (2009):

1. **Usability** – is the *support* understood and usable by the intended users
2. **Applicability** – does the *support* address the key impact factors identified in the Impact Model

The results of the research have been evaluated by testing them to different extents in industrial projects. All of the test-projects have been consulting projects but of different types, including design reviews, new product development, root-cause-analysis / forensic engineering, and training. The evaluation should be seen as an *initial evaluation* (Blessing and Chakrabarti 2009) due to the informal approach and limited number of data. Therefore the findings should primarily be seen as tendencies and indications rather than proofs. A more comprehensive evaluation can be conducted to confirm the findings. This could be done by continuing the logging of R&D resources and change notes in the consumer electronics case company, which would provide additional data points that could give a more accurate picture of the effects of Robust Design implementation. Because there are many noise factors and a limited number of data points (it will take e.g. 5-6 years to get results from 10 projects) the evaluation should be supplemented by interviews with project stakeholders to get a qualitative evaluation of the applicability, usability, and effects of the suggested support.

5.4.1 Usability of the results

The **value** in terms of the usability has been evaluated by investigating whether the design engineers and students who have been presented to the results of the research have understood and used it in their work. In general, the users have received training to be able to apply the proposed methods. Training is seen as a prerequisite for the usability evaluation as it is not expected that the users will intuitively apply the proposed methods.

A direct measure of the understanding and usability has been provided through the exam results of students following the 'Robust Design of Products and Mechanisms'-course at DTU, in which the students are given typical cases from design engineering. In general, exam results have been positive. A further measure of the usability has been to measure the progress over time of the Predictability Index® of projects. If users are able to understand and apply the methods, an improvement of the index should be seen over time. Figure 27 shows that the Predictability Index has improved (lower the better) over a course of six weeks in a project in the consumer electronics case-company.

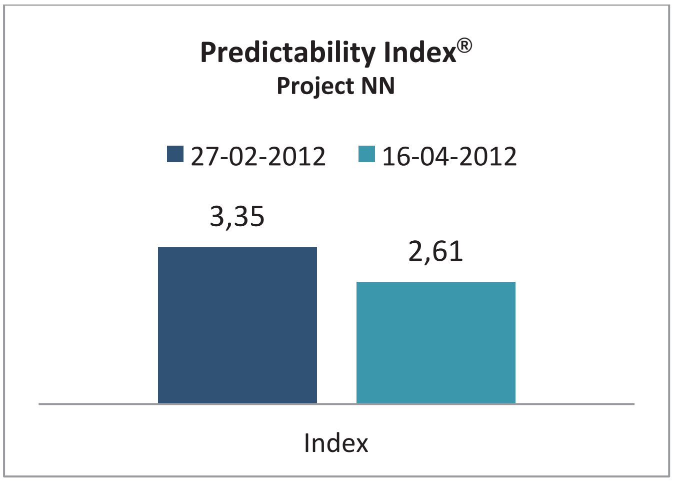


Figure 27. Progress of the Predictability Index® in a project over time

An interesting development related to the use and understanding of the Predictability Index® (PI) was observed in the medical device company described in paper D. Although the PI was intended to be used by the design engineers, it also became popular at management level, most likely because it filled a void in terms of a quantitative and objective measure for the 'goodness' of the development projects.

Another value in terms of usability lies in the simplicity of the Predictability Index®. While discussing how to conduct a training program at a British automotive company, the R&D director said *"I need simplicity. If I am going to roll out an initiative to 2000 design engineers, complex and hard-to-use tools would create noise, frustration and inefficiency. It has to be crisp and simple. If not, it becomes a specialist exercise."*

The primary **limitation** in terms of usability lies in the way Kinematic Design is positioned and defined. If it is presented as a tool, it will be placed alongside many other tools and there is a risk that the intended users will not use it, unless forced to do so. Ideally, Kinematic Design should be positioned as a *mindset* and a *language* such that the design engineers intuitively think and communicate in terms of constraint sets. Correctly constrained designs will be an inherent consequence of such a mindset and the need to measure the PI will gradually be reduced.

5.4.2 Applicability of the results

The applicability of the results is evaluated from an industrial as well as a research point of view.

Value (Industry)

The ability of Kinematic Design to address the key impact factors is demonstrated in Descriptive Study 2. On a more general scale, the applicability has been seen in consulting projects. Kinematic Design and the Principles for Variation Reduction played a central role in identifying and solving the issues in these projects. Kinematic Design is therefore seen as applicable in terms of addressing the suggested impact factors. On a further note, in the medical device company from paper D, the Vice President of the Device R&D Department was asked to evaluate the effects of implementing Robust Design and said: "Now, we have a [project] portfolio, where the large majority are executed at the right cost and with the right feature set, so we no longer have the same problems. Things are running quite smoothly now."

Value (Research)
The value of the results – seen from a research perspective – lies in the focus on a more applied approach to Robust Design. The field is dominated by research on mathematical and statistical issues related to e.g. the use of Design of Experiments and tolerance optimisation and recently also by the development of quality engineering frameworks. The impact model and applicability models are suitable for future research projects to apply and to elaborate upon.

Limitations (Industry & Research)
The proposed methods and principles contribute to reducing the **variation** in Functional Performance, but do not evaluate whether the **nominal** performance will work as intended or whether the product has the correct feature set. As such, it should be remembered that quality engineering also contains other aspects and that a balance between these should be strived for.

A further limitation is the risk of overemphasizing the value and importance of variation reduction and forgetting to see the big picture. It is easy to see the applicability of Robust Design in general and the suggested solutions in particular, as they reduce the costs of non-quality. However, the initiatives themselves also come at a cost. Resources are required for driving the change, initial and ongoing training, specialist support, and not least the time spent on analyses and documentation of the work. At some point, the costs of failure prevention outweigh the costs of failures and therefore an optimum point exists where the total of the failure and failure prevention costs are minimal. Finding this optimum in practice is challenging as there are many hidden costs of both failure prevention and experienced failures. However, it is worth keeping in mind that for certain types of companies (e.g. small companies, companies with a small, local market, companies selling low cost/low quality products) the costs of non-quality may be reasonable compared to a large change management program.

Furthermore, this research only deals with mechanical and electromechanical assemblies. Variation also exists in e.g. software and the way the product is used (intentional and unintentional misuse). These aspects are not included in this research and should be addressed using other means.

Finally, it is worth repeating the observations from the interviews with the companies applying Robust Design. Considerable implementation efforts are associated with any changes to an organisation and this is no exception.

6. Suggestions for further research

Having concluded the research project, ideas for further research have emerged. This section presents suggestions for further research that could build on top of the results of this research or address experienced issues within the field of Robust Design which have not been dealt with in this research:

Right-First-Time using Kinematic Synthesis
The potential benefits of designing right-first-time are obvious. Initial experiences with using Kinematic Synthesis to structure not only the conceptual design, but also the detailed design activities have proven to be positive. Further research into means of managing and communicating intended location schemes between members of the design team in e.g. a top-down approach could prove interesting.

Elaborate on suggested Design Principles
The 15 design principles suggested in this research could be strengthened e.g. by further investigations into costs and benefits, by extending the case examples into a more comprehensive catalogue of examples that can serve as inspiration for design engineers, or by identifying additional principles or sub-principles.

Comparison of Design Solutions
A designer is constantly making decisions between different design alternatives. The Predictability Index® provides support in terms of the predictability of the design alternatives, but does not directly predict the functional performance. It is suggested to investigate how e.g. VMEA and process capability databases can be used in conjunction with Kinematic Design such that the quality of suggested design alternatives can be quantified and predicted, even by typical design engineers.

Customised support
There is an enormous span from the available *development-time-per-interface* in e.g. the medical device industry compared to consumer electronics. The tools and methods applied as part of failure prevention must match the costs of non-quality for the company. Therefore, defining a level-based approach that supports a manufacturer of plastic toys as well as NASA could prove interesting. These companies should not necessarily apply the same set of tools to the same level of detail. The development of a customised support framework for SME's as well as large corporations would be beneficial.

CAD Integration
The process of systematically analysing all interfaces in a design to identify overconstraints and design ambiguities is currently done manually. There are obvious benefits from integrating this task into the design engineer's CAD-software. This would enable the project lead engineer or system architect to define the intended constraint sets for all interfaces in the design in a top-down manner, and feedback from the CAD system would be available in real-time for the design engineer, highlighting overconstraints and design ambiguities and reporting the Predictability Index® of the design. The

CAD integration would support structural and tolerance analysis as force transmission paths and tolerance chains would already be defined. To some extent, CAD integration is already available in commercial software tools like Sigmetrix CETOL and RD&T and is also described by Söderberg et al (1999) and Homann (1998). Care should be taken to ensure that the resulting solutions are also applicable on a generalist level, to ensure the successful adoption.

7. CONCLUDING REMARKS

The PhD-project has personally been a unique opportunity to dive deep into the field of quality engineering in general and robust design in particular. It has given many valuable insights and has introduced me to countless new methods and frameworks. It has allowed me to pursue an interest for teaching in academia at DTU and to engage in fruitful discussion with fellow researchers. I look forward to applying all of this in my future work.

In Valcon we say that we want to create footprints wherever we operate, meaning that is it possible to see where Valcon has been and made changes. I hope that I have set some small footprints within the Robust Design research field that can be seen in future research projects, within the companies that I have been in contact with and within the readers of this thesis.

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9. APPENDED PAPERS

Paper A
A Classification of the Industrial Relevance of Robust Design Methods

Paper B
The Foundation for Robust Design: Enabling Robustness Through Kinematic Design and Design Clarity

Paper C
Robust Design Principles for Reducing Variation in Functional Performance

Paper D
How to Implement and Apply Robust Design: Insights from Industrial Practice

Paper E
A Robust Design Applicability Model

10.1 Paper A

”A Classification of the Industrial Relevance of Robust Design Methods”
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A CLASSIFICATION OF THE INDUSTRIAL RELEVANCE OF ROBUST DESIGN METHODS

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ABSTRACT
The use of Robust Design Methods in industry is limited. Based on statements from industrial surveys and the authors' experience from working with industrial design in industry, it is suggested that the barriers for industrial implementation of RDM is the lack of early-stage methods that can provide the design team with leading and quantifiable metrics in a simple and fast manner.
Using this assumption, success criteria for the implementation of RDM in industry and a classification of the current body of robust design methods are presented. The presented classifications show that only a limited number of methods focus on the reduction on sensitivity to variation and that especially in early design stages, there are almost no leading and quantitative methods available. Existing methods most often rely on data from previous projects and the experience of the design team.
It is concluded, that the low use of RDM in industrial practice can be explained by the lack of operational tools to fulfill the existing Robust Design principles. Consequently, a suitable framework with leading, early-stage, and quantitative methods and metrics must be developed.

Keywords: robust design, reliability, kinematic design, sensitivity, variation

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1 INTRODUCTION

Robust Design Methods (RDM) comprises a set of principles, tools, and metrics that are used to analyze and design products such that they become insensitive to changes in their design parameters. However, surveys have shown, that industrial use of RDM is limited – not only by absolute measures, but also relatively, when compared to the use of other design methods. The purpose of this paper is to 1) identify the criteria that robust design methods need to fulfill in order to be adopted and implemented in industry and 2) to review, classify and discuss to which extent the current body of robust design methods fulfill these criteria. The result of the contribution can be used to identify shortcomings of the current state-of-the-art as well as for pointing out a direction for research and the development of new robust design methods that will become successful in industry.

2 BACKGROUND

Robust Design was first introduced in the 1950's by the Japanese engineer and statistician Genichi Taguchi and was popularized in the 1980's, where it was applied at Boeing and Ford Motor Co. among others (Taguchi et al. 2005). Initially RDM was centered on the concept of quantifying the societal loss due to variation in functional performance and on the use of experimental analysis to select values of design parameters, such that the resulting design became insensitive to changes in the design parameters. Since then, RDM has evolved into a separate research field, including a wide variety of principles and methods.

2.1 Industrial use of RDM

Although RDM literature offers a wide array of principles and methods, surveys show that the application of RDM in industry is limited. In a survey of the Swedish manufacturing industry (Gremyr et al. 2003), 80% of the respondents reply that they work actively to reduce variation between samples of the same product, but only 18% of the respondents use robust design methods, despite that the primary objective of using RDM is exactly the reduction of functional variation.

In the United Kingdom, a study by Araujo et al. (1996) on the industrial use of 31 different product development methods ranks the methods by the degree of use in industry. The list includes 4 Robust Design Methods: Robust Design (Taguchi), Fault Trees, and Design of Experiments (DOE), 3 of which are placed amongst the 4 least used methods (31, 29, and 28 respectively), whereas FMEA is placed as no. 8. This indicates that even though engineering design methods in general may have a low adaptation rate in industry, robust design methods still have a relatively lower use-rate than other methods.

Thornton et al. (2000) have conducted a survey on the use of RDM in US industry, which shows that only 39% of commercial companies "proactively use robust design", meaning that they use it throughout the design process, and that 38% use it reactively to issues that are identified during production ramp-up.

Combining the results of these surveys, it seems that the use of robust design is limited in industry – both in absolute measures and relative to other engineering design methods. Moreover, when it is used, it is often used in the late design stages to solve experienced issues rather than in the early design stages as a method for preventing issues from occurring. This raises a question regarding the barriers for applying robust design methods in industry.

2.2 Barriers for using RDM

Generally, the introduction of new processes and methods in any organization can be a challenge (Araujo 2001). The list of potential barriers is long, but can roughly be summarized as:

- **Organisational barriers:** Fear of change. Lack of organizational support. No promotion of value proposition. Methods are applied wrong. Lack of training. Lack of competence in organization.
- **Method barriers:** Methods are not applicable. Method does not create wanted effect. Efficiency of method (effect vs. time/cost to use). Poor design of method. Lack of appeal. Results are not operational/ usable.

The organizational barriers are generic and well-known. They could be relevant regardless of the method in question and can explain the general lack of usage of structured design methods in industry,

but do not specifically explain why RDM also by relative measures have not been adopted and implemented by industry. This explanation must lie within the methods themselves. In other words, there is an inherent barrier within the available robust design methods that results in the relatively low usage in industry. Several authors within RDM have criticized the methodology for various reasons.
Matthiassen (1997) and Andersson (1996) criticize RDM for not providing support in the early design stages and for having too much focus on statistics and parameter optimization rather than engineering design and support in the conceptual and architectural design phases. Thornton et al. (2000) state, that there is a *"lack of quantitative models that enable a design team to make quick and accurate decisions"* and continues by stating *"that there is large body of literature but the tools are too complex"*. Araujo et al. (1996) claim that the '*tools require experienced or trained staff*' and Gremyr et al. (2003) states that the "*major part of research on RDM has focused on developing statistical techniques*".

2.3 Industrial Success Criteria

The picture described in the previous section, of Robust Design Methods primarily being late-stage, timely to use, and with too much focus in statistics corresponds well with the authors' experience from working with industry – there is an expressed request for simple, objective methods that can be applied as design tools in highly iterative development projects, with constantly changing designs. This critique can be used, however, to describe the success criteria for RDM to be adopted by industry. What makes the popular methods from the surveys popular? What would an ideal robust design method look like, in the eyes of the industry? Based on a combination of the statements from the surveys and the authors' consulting experience, the following success criteria have been established:

1. **Leading indicators.** Many metrics are lagging, meaning that they show what *has happened*, rather than indicate what is *going to happen*. An example of a lagging indicator (sometimes referred to as 'effect indicator') in robust design, is 'production yield'. Leading indicators are preferable because they allow time for design changes. A good leading indicator is associated with a lagging/effect indicator, thereby allowing it to be used as an indicator of the effects of continuing with the current design.
2. **Quantifiable metrics.** Management and engineers want to make data-driven decisions. Therefore, they need quantifiable metrics that are easy to implement and allow for comparison with alternative solutions, previous projects, industrial standards or competitor products. This criteria is also stated by Thornton (2004)
3. **Early-stage application**. The cost of design changes increases exponentially as a development project progresses and metrics and methods that are applicable at an early-stage are therefore preferable. Real-life projects seldom follow a strict linear development process, but rather use frontloading of critical issues. In this paper, 'early-stage' is therefore not defined by the stage in which a method can be used, but rather on the necessary information needed to apply the method (e.g. sketch, architecture, dimensions, tolerances, physical models, etc).

Obviously, other aspects than the ones mentioned here, are also relevant. For example, aspects such as *required training, impact of method* and *resources required to use the method* are relevant, but are more difficult to use for categorization purposes, since they are not inherent characteristics of the method, but rather dependent on how and where the method is applied. They are therefore left out of the analysis.

3 DELIMITATION OF TERMS AND CORRESPONDING METHODS

A wide variety of approaches aiming at an improvement of product quality is available in literature. Well-known are the Failure Mode and Effects Analysis (FMEA) commonly used in the European automotive industry (Bertsche 2008; Kumamoto 2007), lifetime calculations of machine components (Bertsche 2008), or Statistical Process Control (SPC) (MacCarthy, Wasusri 2002). The basic difference between RDM and other approaches is illustrated by means of Taguchi's Quality Loss Function in Figure 1. Traditionally, quality control methods focus on the prevention of product failures in production or use processes. They ascribe any performance within specification limits (between Upper Specification Limit (USL) and Lower Specification Limit (LSL)) as having no loss, whereas a performance outside the specification limits is ascribed a maximum loss, which is illustrated by the red line in the figure. However, even a small variation of geometric properties could lead to a deviation of product performance from its intended value, e.g. the necessary operating force, size of split lines between parts, lifetime, etc. – all of which can be perceived as a loss of quality to the user, but not necessarily a failure, illustrated by the black line in the figure. In general, every variation Δ_0 of a quality characteristic y around the originally planned target value m could lead to a reduction of functionality or quality and in the worst case will damage the company's reputation. Consequently, the occurring variation as well as the resulting monetary loss A_0 should be reduced by means of robust design solutions (Taguchi et al. 2005).

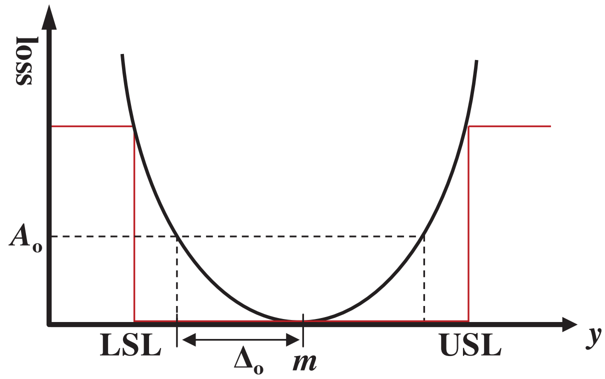

Figure 1. Quality loss function (Taguchi et al. 2005)

By means of Taguchi's Quality Loss Function, Robust Design is delimited from other research fields using the delimitation model in Figure 2. Horizontally, the basic difference between approaches focusing on variation and approaches aiming at the improvement of reliability, i.e. at a prevention of product failures, is shown. Vertically, the field of application is differentiated. Approaches for the control or the improvement of existing production processes are distinguished from approaches used in product development.

In the following, the paper concentrates on approaches applied in different phases of product development. The prevention of failures in production processes, e.g. by means of quality testing, check sheets, data based histograms and pareto diagrams (Ishikawa 1982) or Lean Manufacturing techniques such as visualization of occurring deviations and continuous improvement (Pojasek 2003), are not taken into account. The same applies to SPC approaches (MacCarthy, Wasusri 2002) for the control of production variation. Within product development, the main focus of the paper is on Robust Design approaches, as indicated in Figure 2. But as even literature on Robust Design usually also refers to corresponding methods from the field of Reliability Analysis (Hasenkamp et al. 2009), differences as well as the overlaps between Robustness and Reliability need to be further clarified.

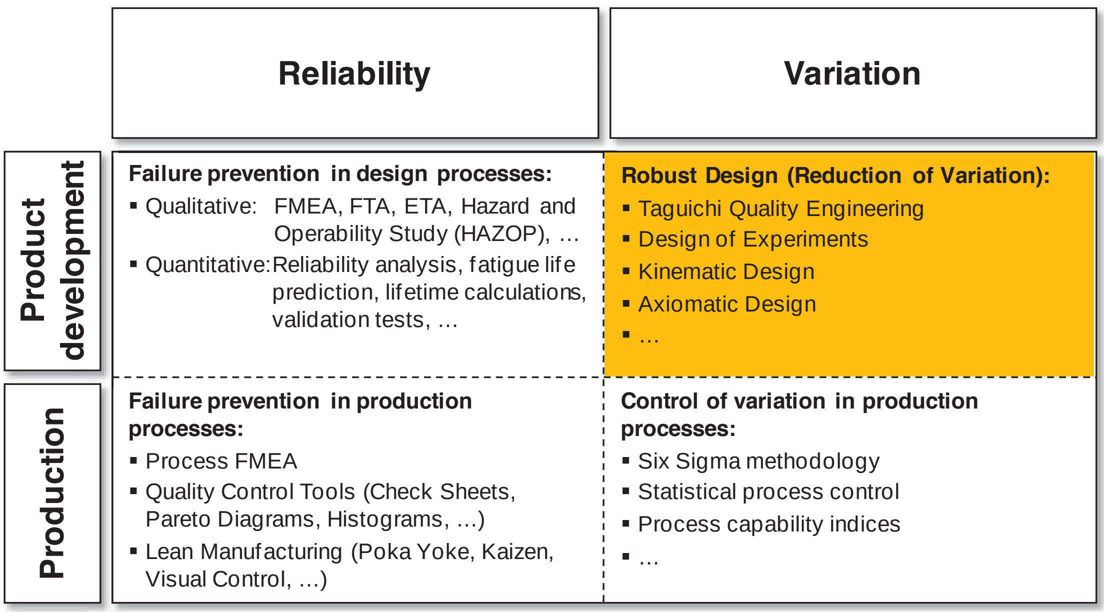

Figure 2. Delimitation of terms and corresponding methods

4 ROBUST DESIGN METHODS

4.1 Classification of RDM – state of the art

Previous literature reviews on RDM have to some extent provided an evaluation and classification of Robust Design Methods. Hasenkamp et al. (2009) distinguish between robust design principles, practices and tools. Based on the distribution of the reviewed contributions, it is concluded that there is a lack of 'practices' that describe what needs to be done. A wide array of contributions are grouped depending on their subject focus, e.g. the quadratic loss function, noise factors, experimental designs, but the details regarding how each subject is treated are not analyzed. Other authors evaluate the advantages and disadvantages of selected RDM's; for example, Lough et al. (2009) evaluate risk assessment techniques and Matthiassen (1997) gives a systematic description and evaluation of the dominant methods within robust design, and reaches the conclusion that there is a lack of early-stage methods.

For the classification, principles, methods and metrics are described. But seeing that the classification categories are leading/lagging, quantitative/qualitative, applicability in early/middle/late stages, it is only meaningful to classify the metrics and methods. Robust Design principles that describe ideas of how a design should be, but do not provide methods or metrics would not be possible to classify by any of the selected categories.

4.2 Robustness vs. Reliability

Robust design in its pure form focuses on the reduction of variation in functional performance. However, in literature, RDM are connected to a variety of methods and fields with objectives that differ in a number of ways. The most common connection seen is the one between robustness and reliability (Jugulum, Frey 2007). Prior to a classification of the individual robust design methods, the differences between robustness and reliability are clarified based on the delimitation model in Figure 2. Whereas a robust product ideally reacts insensitive towards all occurring variations within the processes of the product life cycle, the definition of reliability states (Bertsche 2008):

> *Reliability is the probability that a product does not fail under given functional und environmental conditions during a defined period of time*.

Consequently, Reliability approaches focus on the prevention of defective parts in production or the prevention of product failures when the product is shipped. Thereby, the product is usually interpreted as a parallel or serial structure of components. Based on a description of occurring failure modes and based on available information of failure rates, the overall failure probability of the system is calculated (Bertsche 2008). Risk Management techniques extend the analysis further to a consideration of resulting consequences for the user and the environment (Lough et al. 2009, Kumamoto 2007). Table 1 presents an overview of Reliability approaches. It contains commonly used methods such as the FMEA, the FTA, lifetime calculations for machine elements or product qualification tests (Bertsche 2008; Kumamoto 2007). For a comprehensive overview, these approaches are complemented by methods specifically conceived for the application in early design phases. Examples are statistically based lifetime calculations (Gandy et al 2006) or the assessment of product reliability based on a functional model within the Function Failure Design Method (FFDM) (Lough et al. 2009). Each method has been classified with respect to the success criteria from Section 2.3. The classification is done based on the authors' review and knowledge of RDM literature.

4.3 Classification of RDMs

In Table 2, Robust Design Methods focusing on the reduction of variation in functional performance have been classified in the same way that the methods focusing on product failure were classified in Table 1. The included methods have been selected in a semi-structured manner, by including the methods typically mentioned in robust design literature as well as methods mentioned in robust design literature reviews and surveys.

In the table, robust design frameworks such as Variation Risk Management (Thornton 2004) and Design for Six Sigma (Creveling et al. 2002) have not been included, because they are seen as management frameworks with underlying methods, which either are already included in the classification tables or are out of scope (as defined in Figure 2). Robust Design Principles, described by e.g. Matthiassen (1997) and Andersson (1996), are not methods, but are still included in the table.

By nature, they are leading and applicable in early stage, but they cannot be quantified. For example, a principle such as ‘design for self-reinforcement’ serves as a guideline, but not an indicator or metric.

Table 1. Methods to control failure probability

Method		**Tool**	**Leading / lagging**	**Quantifiable metric**	**Quantitative / qualitative**	**Necessary information (Early/late application)**
FMEA **(Bertsche 2008)**	Systematic procedure for the preventive assessment of possible failure modes	Form sheets	**Leading**	RPN	qual.	**Early** Expert experience
ETA (qualitative) **(Kumamoto 2007)**	Diagram to examine subsequent failure modes	/	**Leading**	/	qual.	**Early** Expert experience
FTA (qualitative) **(Bertsche 2008; Kumamoto 2007)**	Diagram to examine subsequent failure causes	/	**Leading**	/	qual.	**Early** Expert experience
HAZOP **(Kumamoto 2007)**	Examination of risk based on standardized guide words	Functional model / Lists of guide words	**Leading**	/	qual.	**Early** Expert experience
ETA (quantitative) **(Kumamoto 2007)**	Calculation of failure probability based on boolean logic	/	**Leading**	Probability of product failure	quan.	**Middle** - product architecture - subcomponent performance
FTA (quantitative) **(Bertsche 2008; Kumamoto 2007)**	Calculation of failure probability based on boolean logic	/	**Leading**	Probability of product failure	quan.	**Middle** - product architecture - subcomponent performance
FFDM **(Lough et al. 2009)**	Evaluation of the dependency of function failures	Functional model	**Leading**	Probability of function failure	quan.	**Middle** - bill of materials - historical data on function failure
Structural Integrity **(Geere, Goodno 2008)**	Calculation of stresses and strains in product components	Simulation software, hand calculations	**Leading**	Safety factor wrt. failure criterion	quan.	**Middle** - Material data - Load data - Component geometry
Probabilistic Risk Assessment (PRA) **(Kumamoto 2007)**	Evaluation of accidents for existing systems (usually complex plants, etc.)	Methodology	**Lagging**	Risk profiles	qual.	**Middle** - Product - Possible failures and accidents
Lifetime calculations **(Bertsche 2008)**	Lifetime prediction for mechanical elements based on empirical models	Damage accumulation hypothesis	**Leading**	Lifetime prediction	quan.	**Middle** - load spectrum - tolerable material load (Wöhler)
Variation based lifetime calculations **(Gandy et al. 2008)**	Stochastic lifetime prediction for mechanical elements	Damage accumulation hypothesis	**Leading**	Probability of lifetime	quan.	**Middle** - load spectrum - tolerable material load (Wöhler) - property variation
Qualification Tests **(Bertsche 2008)**	Empirical verification of lifetime based on different load testing conditions	Test system	**Lagging**	Lifetime prediction	quan.	**Late** - Prototype - detailed knowledge about failure mechanisms and existing load

Table 2. Methods to control variation in functional performance

Method		Tool	Leading / lagging	Quantifiable metric	Quantitative / qualitative	Necessary information (Early/late application)
Taguchi Methods **(Taguchi et al. 2005)**	Optimising parameter values and tolerances wrt. the sensitivity of each design parameter to obtain low variation in functional performance	N/A	**Lagging**	N/A	quan.	**Late** - Parameter values - Process capabilities
Design of Experiments **(Taguchi et al. 2005)**	Structured tests and simulations to optimise parameter values wrt. The signal-to-noise ratio	DOE procedure	**Lagging**	S/N-ratio (Signa-to-noise)	quan.	**Late** - Parameter values - prototypes or simulations
Axiomatic Design Information and Independence Axioms **(Suh 2001)**	1) Identification of design parameters controlling more than one functional requirement 2) Identification and reduction of the information contributing to a functional requirement	Coupling Matrix and No. of design parameters	**Leading**	N/A	qual.	**Middle** - Design parameters - functional requirements
Kinematic Design, Design Clarity, Minimum Constraint Design **(Ebro et al. 2012; Söderberg, Lindkvist 2002)**	Quantifying the clarity and quality of design constraints as well as the mobility of the design	Kutzbach Equation and Robustness Cockpit	**Leading**	Mobility	quan.	**Early** Product Architecture
Locating Schemes **(Söderberg et al. 2006)**	A quantification of the transfer function, converting the gradient into a metric	RD&T Software, Locating schemes	**Leading**	Instability & Quality Appearance Indices	quan.	**Middle** - Design parameters - functional requirements
Robust Design Principles **(Matthiassen 1997; Andersson 1996)**	Collection of good design principles, that lead to robust design.	N/A	**Leading**	N/A	N/A	**Early/Middle** (Depending on the individual principle)

5 ANALYSIS OF RESULTS

Ultimately, the objective of robust design research is the application of suitable RDM in industrial practice. Based on the identified success criteria for an industrial application, the elaborated classification needs to be visualized to give a structured overview of available approaches. Based on the visualization, findings and necessary extension to available RDM are discussed.

5.1 Classification Model RDMs – Visualization

A visual representation of the classification in Tables 1&2 is shown in Figure 3. First of all, two of three success criteria for the industrial application of RDM are used to define the basic framework of the representation. Vertically, leading and lagging methods are distinguished. Horizontally, the methods are placed according to when in the development process they can be applied (early, middle, late). Finally, the third criterion is visualized by means of round or rectangular shapes, i.e. the distinction between qualitative approaches relying on subjective expert assessments and quantitative, objective methods. In this way, the classified methods from the fields a) Reliability Analysis and b) Robust Design can be assigned according to their applicability and their value within design.

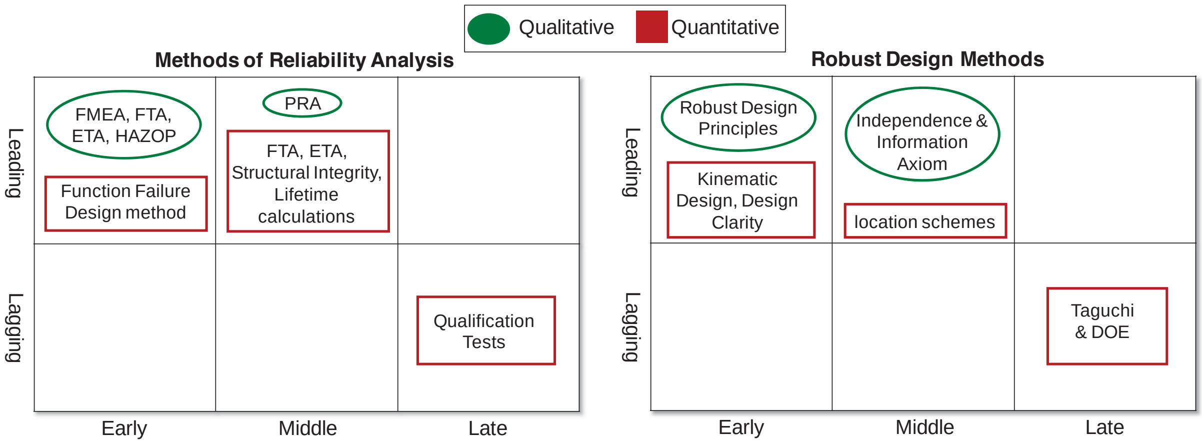

Figure 3. Visualization of classifications

5.2 Discussion

The visualization of the classification in Figure 3 illustrates the current body of available approaches for an analysis and improvement of Reliability as well as of existing RDM. The mapping of the methods gives the designer a structured overview of the available RDMs and assists in selecting a method, which fits with the type of analysis and result that is wanted. On this basis a number of observations can be made:

– First of all, the designer can distinguish between methods refering exclusively to reliability, i.e. failure probability or predicted lifetime, and methods focusing on the reduction of variation. On the whole, there are no distinct 'white-spots' on the map, where no methods are available. However, it is the impression of the authors that RDM-literature focuses on FMEA, DOE and Taguchi methods, none of which fulfill the industrial criteria derived on section 2.3.

– Especially, existing quantitative approaches for an assessment of reliability largely depend on available information pertaining past product failures, i.e. empirically described failure criteria, databases with existing failures or tests. This leads to the tendency that reliability is usually calculated for well known products or large systems as well as in late design phases, when reliability data of different subcomponents is available. Examples are machine elements (Bertsche 2008), power plants, and train transport (Kumamoto 2007). Even approaches that explicitly refer to the necessity of an early, quantitative assessment rely on historical data. Whereas the consideration of possible variation in lifetime calculations is based on available damage accumulation hypotheses, the FFDM uses archived information of existing products.

– The same problem applies to qualitative approaches classified as leading. Qualitative methods in the field of reliability as well as Robust Design are based on subjective expert assessments. Thus, the obtained results also largely depend on detailed experiences and subjective estimations of the designer in charge. Used indicators, e.g. the Risk Priority Number within the FMEA, could somewhat also be classified as lagging.

– A main shortcoming of the current body of available methods is that no objective and quantifiable indicators exist for an early and easy to apply evaluation of the systems robustness in highly iterative development projects. The right hand side of Figure 3 shows that the current approaches, also applied in industry even just to a limited extent as discussed in section 2.1, focus on late design stages. Approaches, such as DOE and Taguchi's Quality Engineering, are based on experimental analyses of existing prototypes and consequently are lagging indicators which only are applicable in the middle or late stages. This makes it challenging for a designer to make data-driven decisions in early design stages.

Consequently, a shift in focus to methods such as kinematic design and design clarity (Ebro et al. 2012) that provide an easy to calculate, objective and quantifiable robustness metric could be valuable for the field. In general, the conversion of existing Robust Design principles that describe the basic idea how a design should be (Matthiassen 1997; Andersson 1996) into operational methods with corresponding metrics could be a subject for further research.

Another important conclusion for further research, drawn from the classification, is the lack of methods to analyse the impact of noise factors. For the choice of suitable RDMs, the existing dependencies between occuring disturbances and the products performance need to be described by a suitable transfer function as early as possible. Available approaches, e.g. Taguchi's Quality Engineering, strongly rely on DOE, thus cannot be applied until a first prototype exist. In general, the establishment of transfer functions in different design stages is usually not explained in a detailed manner (Hasenkamp et al. 2009; Jugulum, Frey 2005). Even qualitative approaches are either exclusively based on expert assessments, e.g. the Variation Mode and Effects Analysis (Johansson 2006), or refer to specific applications, e.g. the analysis of a dish washing machine (Pons, Raine 2005). To analyze the wide variety of influencing factors in the product life cycle (Eifler et al. 2012), a comprehensive approach for a systematic assessment of existing noise factors and the analysis of existing dependencies in life cycle processes is elaborated within the Uncertainty Mode and Effect Analysis (UMEA) (Engelhardt et al. 2011).

6 CONCLUSION

The use of Robust Design Methods in industry is limited. Based on statements from industrial surveys and the authors' experience from working with industrial design in industry, it is suggested that the barriers for industrial implementation of RDM is the lack of early-stage methods that can provide the design team with leading and quantifiable metrics in a simple and fast manner. Using this assumption, success criteria for the implementation of RDM in industry and a classification of the current body of robust design methods are presented.

The presented classifications show that actually only a limited number of methods focus on the reduction on sensitivity to variation, i.e. product robustness. Instead, commonly used methods either focus on the prediction and prevention of failures, i.e. reliability, or on the control of production variation. Furthermore, the surveys' statements are confirmed. Especially in early design stages, only a limited number of leading and quantitative methods is available. Existing methods most often rely on data from previous projects and the experience of the design team or require extensive information on failure criteria, parameter values, tolerances, etc. Consequently, they cannot be applied until later design stages which makes design changes significantly more costly.

It is concluded, that the low use of RDM in industrial practice can be explained by the lack of operational tools to fulfill the existing Robust Design principles. Without the benefit of a quantifiable metric it is usually unclear to which extent a principle has been followed. Consequently, a suitable framework with leading, early-stage, and quantitative methods and metrics must be developed. Moreover, the concept of the transfer function must be converted from a principal and theoretical representation to an operational tool. These extensions of the current body of RDM needs to be embedded in a coherent Robust Design process that takes into account the dependencies between different design models and can gradually be detailed in every design stage.

ACKNOWLEDGMENTS

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9.2 Paper B

”The Foundation for Robust Design: Enabling Robustness Through Kinematic Design and Design Clarity”

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THE FOUNDATION FOR ROBUST DESIGN: ENABLING ROBUSTNESS THROUGH KINEMATIC DESIGN AND DESIGN CLARITY

Martin Ebro, Thomas J. Howard, Janus Juul Rasmussen

Keywords: robust design, reliability, sensitivity, axiomatic, mechanism,kinematic, ambiguity, design clarity

1. Introduction

Robust Design Methodologies (RDM) focus on developing engineering designs whose functional performance are insensitive to the geometric variation they are subjected to during production and use. Robust design literature offers comprehensive methods – quantitative as well as qualitative - for analysing and describing the robustness of a given design. Examples include Taguchi's Signal-to-Noise ratio [Wu 2000], differentiation of the so-called *transfer function* [Eifler 2011], Failure Modes and Effects Analysis (FMEA) [Bertsche 2008], and Fault Tree Analysis (FTA) [Bertsche 2008]. These methods are useful for analysing a given design and estimating failure rates and sensitivity to variations and hence take mitigating actions or optimise the design by adjusting the design parameters. However, it is often pointed out, that RDM lacks tools and methods for early-stage design and for synthesis of alternative solutions [e.g. Andersson1996]. The aim of this contribution is: 1) to describe why the principles of **kinematic design** and **design clarity** should be applied prior to other robust design activities, 2) to provide a step-by-step procedure that can be used during early-stage design to quantify the degree of adherence to these principles and 3) to highlight **ambiguity, abruptness** and other factors that affect the functional performance of a design. The principles described will be accompanied by a simple tool that can be used by engineering designers during early-stage (as well as detailed) design to quantify the clarity of a design. Finally, the principles and tools will be applied to two cases.

The research presented in this paper comes with over 30 years of combined experience of applying RDM in industry and therefore attempts to portray the industrial perspective. The paper therefore focuses on the dominant methods used in industry and some of the critical Design for Robustness issues.

2. State of the art: The correlation between robust and kinematic design

Taguchi is often refered to as one of the key players in robust design. Taguchi states, that there is a loss associated with *any* deviation of a performance characteristic (e.g. the force needed to push a button) from its target value and not just when performance lies outside the specified tolerance limits [Lochnar&Matar 1990]. In other words, an ideal robust design should have no variation in functional performance when a design parameter (e.g. the diameter of a hole) is varied. There are a finite number of sources of variation for design parameters. Although they are described and categorised differently in different literature, the sources are here described as:

- Production tolerances (e.g. due to variation in shrink percentage, process parameters etc.)

- Assembly tolerances (e.g. due to clearance around mounting screws)
- Load deformations (e.g. due to user loads, wind loads, gravity, etc)
- Variation due to ambient conditions (e.g. due to change in temperature, humidity, etc)
- Variation over time (e.g. due to wear, creep, swelling)

There is a wide variety of Robust Design Methodologies that describe how the influence of these variations can be reduced. They can be divided into categories depending on the information necessary to apply them, the output type (quantitative/qualitatitive), etc.. In [Eifler 2011], a classification of methods is presented. The typical methods focus on identifying and evaluating the design parameters either by experiments (Design of Experiments (DOE)) or analysis and hence using statistics to adjust the design parameters in order to improve the robustness of the design. However, in order to be able to conduct experiments, physical prototypes must be available and to set up an analytical (or numerical) parameter study, e.g. using computer simulations, calculations etc., the design must have reached a level of maturity where the design parameters have been identified and quantified. Furthermore, both the analytical and the experimental approaches are time-consuming, which presents a challenge during early-stage design, where the design changes so frequently that any analysis must be fast to conduct in order to be applicable. As a consequence, the robustness activities are not conducted until the design has reached a level where the conceptual solutions are somewhat frozen, even though the effects of *conceptual robustness* are greater than parameter optimisation. Despite this, there seems to be a lack of Robust Deisgn Methods for the design engineer to use during the early phases of product development. In Figure 1, the typical Robust Design Methods used in industry are placed according to the product development phase they are typically applied in, according to the authors' experience. It can be seen, that there is a lack of methods available for concept development and system-level design – the methods Kinematic Design and Unambiguous Design are new and will be presented later.

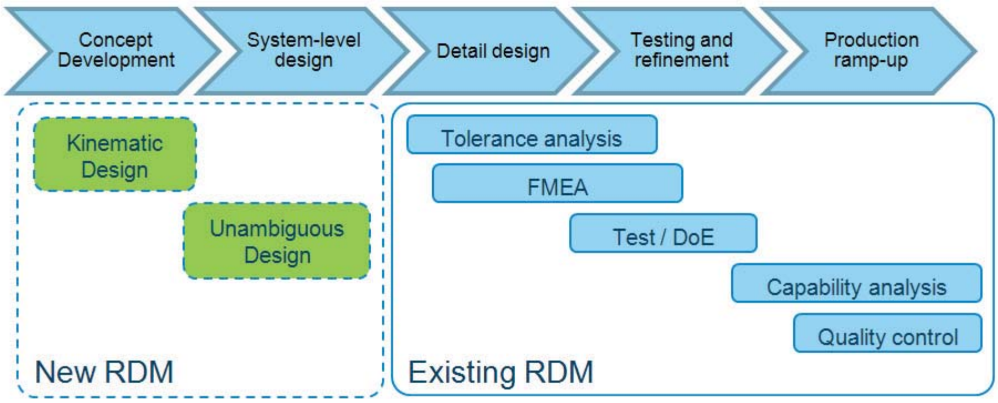


Figure 1 – The generic product development process from Ulrich &Eppinger[Ulrich &Eppinger 1995] with Robust Design Methods placed according to the authors' experience of when they are typically applied in industry (In reality, the process is more iterative). The methods shown in the dashed boxes are new.

In some robust design literature [e.g. Andersson 1996] it is pointed out that the existing Robust Design Methodologies are difficult – if not impossible – to apply to early-stage designs. Andersson argues, that current methods focus on analysis rather than synthesis, and that the methods are difficult for the typical design engineer to apply, due to their statistical and theoretical nature. Andersson continues through a list of design principles for the designer to use during early design stages. The principle of kinematic design is mentioned as a principle that results in robustness.

Pahl and Beitz [Pahl&Beitz 2007] provide a somewhat similar principle referred to as *design clarity.* However, it is not elaborated upon and developed into an operable tool for the design engineer to use. Downey [Downey 2003] describes a procedure for *smart assemblies,* which are also based on kinematically correct constraints.

Kinematic Design [Myszka 2005] is a design principle which focuses on obtaining a design which is not *overconstrained,* i.e. having more constraints than needed. Overconstrained designs entail a series of effects, some of which contribute to variation in functional performance. If a design is overconstrained it will be more sensitive, with greater variations in functional performance caused by undesired variations of design parameters.
In Axiomatic Design [Suh 2005] there are two axioms –the independence axiom and the information axiom. The latter states, that *information* should be minimized in order to obtain robust designs, e.g. by reducing the number of design parameters that influence a given functional requirement. By nature, a kinematically overconstrained design is also a design with the potential for reducing the information content (in accordance with axiomatic design guidlines), since one or more constraints potentially can be removed.
It is seen, that there is a correlation between robust design and kinematic design in the sense that kinematic design is a means – among others – to obtain robust design. However, the principles are not elaborated upon and developed into systematic design tools to be used by the designer. The authors of this article, having worked with a wide array of product development projects in industry for more than a decade, have not yet seen kinematic design systematically applied in early phases of engineering design.
In some areas of engineering design, variation in functional performance is extremely important, e.g. measurement equipment and production equipment such as mills and lathes. Performance variation in these applications will result in increased measurement uncertainty and production tolerances, respectively. In robot and mechanism design, with many moving parts, overconstraints can result in jamming mechanisms, excessive loads (and hence product failures), noise and vibrations. Design guidelines for these types of products are actually based on kinematic principles and are called Exact Constraint Design, Minimum Constraint Design etc. One could argue, that it is expensive to apply principles from high-precision products on e.g. consumer products and that it would therefore only be viable to apply these principles to designs involving either high cost or extreme precision. However, kinematic design is merely a question of design principles, and as stated below, kinematic design principles can reduce tolerance requirements and hence production costs are reduced.
An aspect only rarely covered in literature is the aspect of ambiguity. Even though a design is kinematically correct designed in its nominal state, variation of the design parameters can change the interfaces and constraints of the design. For example, an extra constraint can be introduced this way, thereby reducing the mobility of the design. Alternatively, a constraint can switch from one surface to another, which obviously contributes to variation in functional performance. The aspect of ambiguity will be described in more detail later.
Concluding, current state-of-the-art contains many Robust Design Methods to be used for in-depth analyses of how the functional performance is affected by variations in the design parameters, but it lacks a simple, operable method for quantifying the clarity (or ambiguity) of the design. This means that there is a risk of sub-optimising the robustness of a design, which is conceptually sensitive, because it does not adher to the principles of Kinematic Design and Design Clarity.

3. Kinematic design at system level: Mobility

Kinematic design is normally used for designing mechanisms. For a mechanism, it is important that the system has the correct mobility. The mobility is calculated by using the Kutzbach-Gruebler formula, which uses the constraints and the number of elements in a system as inputs and results in a number describing the so-called mobility of the system, i.e. whether the system has the ideal number of constaints. Note that the formula can also be applied to static systems – the only difference being that the intended mobility is equal to 0.
The Kutzbach-Gruebler [Boe 1997] formula states:

$$M(3D) = 6(n-1) - \sum U - \sum F_{id} \qquad M(2D) = 3(n-1) - \sum U - \sum F_{id}$$

Equation 1 – The Kutzbach-Gruebler formula for a 3D and a 2D mechanism. M = system mobility, n = number of links/bodies, U = number of constraints, F_{id} = number of identical freedoms.

For a mechanism, it is crucial that the system mobility according to the Kutzbach-Gruebler formula is correct, otherwise the mechanism may jam, experience noise, vibrations, wear, and/or excessive internal forces (also called parasitic loads), due to constraints 'fighting against' each other.

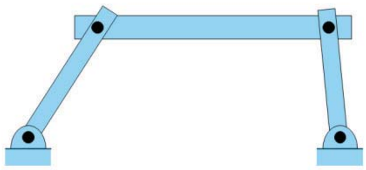
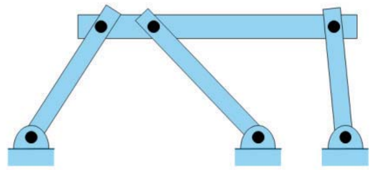
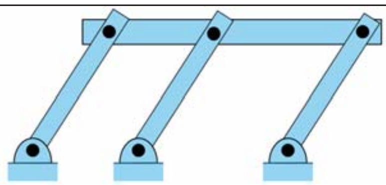
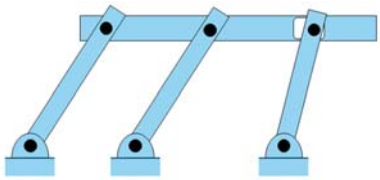
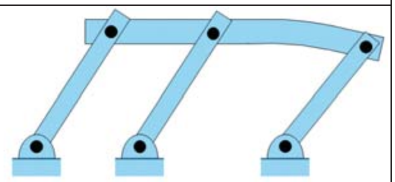
<table>
<tr><td colspan="3">
Four-bar linkage mechanism with mobility = 3(4-1)-4*2=1, meaning that it has 1 degree of freedom, i.e. one input (such as a motor) will completely define all motions of the mechanism.</td><td colspan="3">
Five-bar mechanism with mobility = 3(5-1)-6*2 = 0, meaning it is fully constrained. If an input (such as a motor) is also applied, it will be overconstrained.</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="6">Mechanisms with mobility = 3(5-1)-6*2 = 0. Although the mechanisms are fully constrained, movement is still possible if
• Certain geometric requirements are fulfilled, the links with fixed ends must remain parallel at all times requiring tight toletances of lengths and joint positions (Left)
• Sufficient play is provided in the joint(s) (Middle)
• The link(s) have sufficient flexibility (Right)</td></tr>
</table>

Table 1 – Examples of applying the Kutzbach equation

In Table 1, an ideal kinematic linkage system is shown along with a series of designs that are overconstrained, if an input is also applied. It is seen how an overconstrained design must be compensated by one or more of the following:

- **Tolerances (Bottom left)**. In certain cases, an overconstrained mechanism can still be mobile, if it is produced with tight tolerances.
- **Clearance (Bottom middle)**. If the joints are designed with sufficient play, the mechanism can become mobile. At some point this clearance will transcend into an actual degree of freedom.
- **Flexibility (Bottom right)**. If the links in the mechanism are made of a flexible material, the mechanism can become mobile.

All of the above mitigative actions lead to an increase in functional performance variation or increased cost. Increased clearance in the bearings lead to greater variation in the position of the links, increased flexibility leads to higher deflections, when parts are exerted to loads, and tightened tolerances lead to increased production costs. It is important to mention, that many everyday designs are overconstrained, e.g. a ball bearing. In other words, designs may still function even though they are overconstrained, but they will always have to be compensated by one of the above principles (the balls for ball bearings are produced with extreme tolerances).

During early-stage design, often only a sketch of the design principle is available. However, kinematic design can easily be applied at this stage. To illustrate this, Figure 2 shows a principle for a windturbine with a shaft, a coupling a gearbox and a base (not shown). At this stage, it can be seen that this principle is overconstrained by 5, meaning that 5 constraints must be removed to obtain ideal mobility. This can be done in different ways, e.g. by replacing the current coupling which has 6 constraints, with one that only constrains the axial rotation (an Oldham-coupling, for example). Many alternative solutions can be synthesized in this way.

Body mobility											
Joint	ID	Name		X	Y	Z	Rx	Ry	Rz	F	U
1-2		Base	Shaft	0	0	1	0	0	1	2	4
2-3		Shaft	Coupling	0	0	0	0	0	0	0	6
3-4		Coupling	Gearbox	0	0	0	0	0	0	0	6
4-1		Gearbox	Base	0	0	0	0	0	0	0	6
N			4	Sum of constraints:							22
Fid			0								
No. of inputs			1								
B			-4	B(3D) = 6*(N-1)-Fid-Sum(u)							
Mobility			-5	M = B - Inputs							

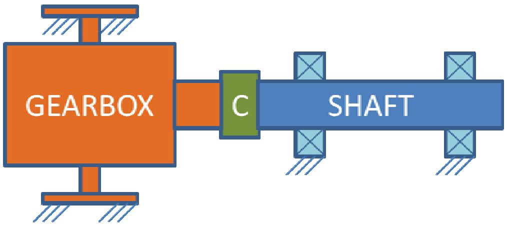


Figure 2 – Kinematic analysis of a windturbine-design. The mobility is -5, meaning that 5 constraints have to be removed to obtain ideal mobility.

By using the Kutzbach-Gruebler formula, the design engineer has a simple and fast tool to improve robustness in early-stage design. Efforts should be made to obtain a conceptual design where the mobility is as intended. Note that the Kutzbach-Gruebler formula does not need any design parameters or numeric values. Only a design sketch like the ones shown in Figure 2 are needed and hence it can be used at early design stages.

It should be noted, that the Kutzbach-Gruebler formula can also be used during the concept phase as a synthesis tool. By altering the number and type of constraints and links, a systematic array of concepts can be derived. As a final note, it is important to stress the difference between the intended constraints and the actual constraints. The procedure sketched above is merely a way to ensure that the intended constraints result in the desired mobility. Later in the design process, a review must be made to ensure compliance between the intended constraints and the actual constraints. This is done by using tolerance analysis, structural analysis etc. and is not covered in this paper.

Concluding, it has been shown that there is a correlation between the kinematic mobility and the robustness of a design. Thus, the mobility is a simple way to quantify the robustness of the design at an early-stage – the more overconstraints a design has, the more it will be prone to variations in functional performance.

4. Kinematic design at interface level: Design Clarity

Once the system level architecture is defined, focus is shifted to the individual interfaces between the components in the product. Here, the Kutzbach-Gruebler equation can not be used in its pure form. However, the concept of ensuring that there are no superfluous constraints is still valid. All interfaces in the product should systematically be evaluated using a step-by-step process, thereby giving an overview of the interfaces that could be sensitive to variations.

Design Clarity Procedure

1. Identify interfaces, e.g. in an interface matrix. The result of this is an overview of all components that have functional surfaces against eachother.
2. Specify *intended* constraints for each interface. This can be done in a simple table like the one shown in Figure 3. For example the intended interface between a shaft and a journal bearing would be to have 1 free rotation (RZ) and the 5 remaining degrees of freedom (DOF) constrained.

Intended Degrees of Freedom		
X	Y	Z
0	0	0
RX	RY	RZ
0	0	1
0 = constrained, 1 = free, -1 = overconstrained		

Actual Degrees of Freedom		
X	Y	Z
0	0	0
RX	RY	RZ
-1	-1	1
0 = constrained, 1 = free, -1 = overconstrained		

Figure 3–A description of the a) intended and b) actual constraints of a given interface. X,Y, and Z are the three translational DOFs. RX, RY, and RZ are the three rotational DOFs.

3. For each interface, specify the *actual* clarity of each individual DOF using Table 2 as a reference. Each of the ambiguity principles that are not adhered to is regarded as a an extra constraint in the relevant DOF.

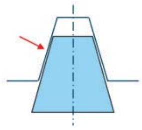
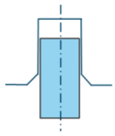
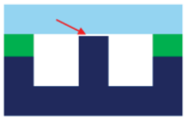
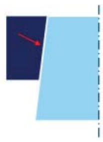
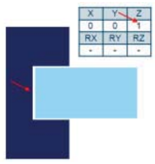
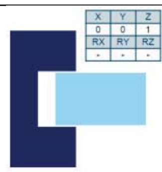
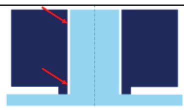
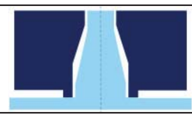
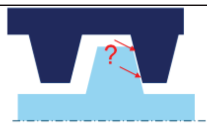
ID	Type of ambiguity	Example	Solution
A	**Angled interface.** Coupling between angle, width and position of part.		
C	**Clearance < n*production_capability.** Risk of an unwanted constraint due to part variations.		
D	**Draft on interface element.** Draft angle defines positioning.		
F	**Flash.** Flash acts as interface element. Misplacement of component.		
I	**Intended not realized.** Loss of overview e.g. wrt. tolerance and structural analysis		
L	**Large surface.** Increases demand on form tolerances.		
M	**Multiple surfaces constrain same DOF.** Loss of overview. Parasitic loads. Increase in tolerance demands.		
R	**Round.** Round acts as interface element. Misplacement of component.		
S	**Shift (abrupt) of interface.** Sudden change of contact point		

Table 2 – Principles of clarity

4. List functional performance requirements and the design parameters that contribute to the functional performance – change design to make parameters obsolete
5. Commence using traditional Robust Design Methodologies to optimize remaining parameters.

The consequences of not having clarity in the design are:

- **Abrupt functional changes**. An abrupt functional change is defined as a change of function due to an infinitisemally small variation of a design parameter.
- **Variation in functional performance,** e.g. component placement, required assembly forces, etc.
- **Reduced precision in tolerance analysis.** If the constraints are ambiguous, tolerance chains will also be ambiguous.
- **Reduced precision in structural analysis.** If the constraints are ambiguous, exact constraints for the structural analysis cannot be defined.

An overview of the constraints in the entire system can be valuable to e.g. the project mangager, or for a project review team, wanting to ensure that all interfaces have been reviewed. An example of this is shown in Figure 4, where each row constitutes an interface, and is followed by the intended and actual DOFs. Any discrepancy between the two results can be visualised by e.g. coloring. The current ambiguity of the design can be summed up simply by adding the number of ambiguities in each of the interfaces.

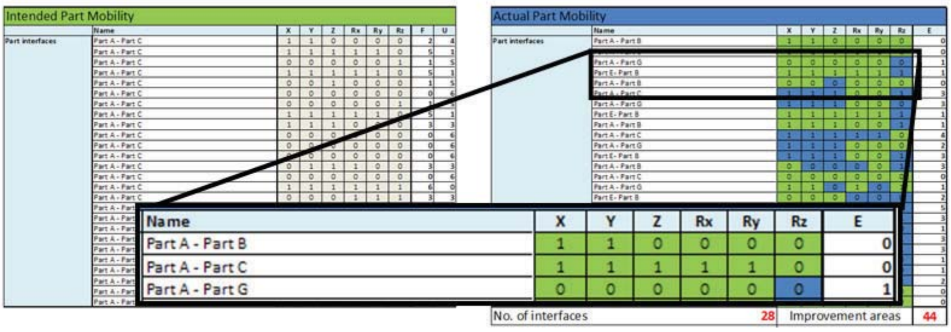


Figure 4–Overview of all interfaces in the product. Each row contains an interface, The left table contains the intended DOF. The right contains the actual DOF. If the actual DOF is different from the intended DOF, the cell is colored to mark that there is a potential robust design improvement. In the bottom row, the overall ambiguity is quantified.

Concluding, the method is fast and simple to use for the design engineer, and hence it is possible to use it during synthesis of the detailed design. It has been shown how the design clarity and robustness are correlated and how the design clarity can be quantified.

5. Kinematic Design and Design Clarity – primers for robust design

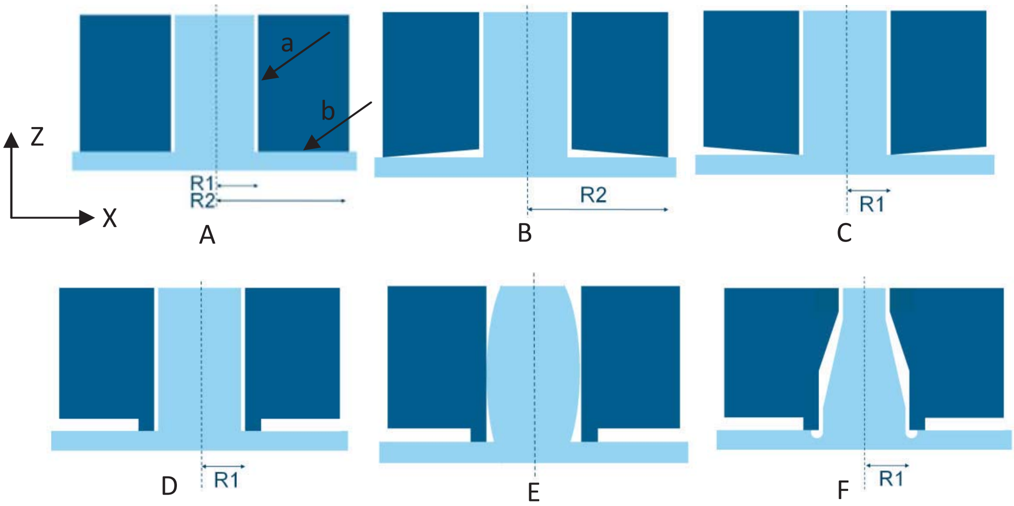
The effect of quantifying and optimising the mobility and the clarity of the design will be a reduced variation in functional performance due to the combination of a more precise identification of the design's functional surfaces and influencing design paramaters and the following reduction of the number of design parameters. In other words, a design with an ideal mobility and an ideal set of constraints, will perform in a more consistent and predictable manner than a similar design which is overconstained and ambiguous.

The subsequent task of quantifying and optimising the robustness of the design using traditional Robust Design Methods, will naturally be simpler to carry out on a design with ideal constraints and low ambiguity. Furthermore, testing and ramp-up of the design will become simpler due to the improved repeatability of the design. This can help reduce the development time and increase the precision of the project execution.

6. Cases

Case 1: Gearwheel

The case is based on a gearwheel which revolves around a center pin – see figure 5. The step-by-step procedure is used. **Step 1** is elementary, since there are only 2 parts. In **Step 2**, it is seen that the intent of the design is to constrain all degrees of freedom except the axial rotation RZ. This is added to



Intended Degrees of Freedom		
X	Y	Z
0	0	0
RX	RY	RZ
0	0	1
0 = constrained, 1 = free, -1 = overconstrained		

Actual Degrees of Freedom		
X	Y	Z
-3	-3	-3
RX	RY	RZ
-1	-1	1
0 = constrained, 1 = free, -1 = overconstrained		

Figure 5 – A gearwheel (dark part) runs on a center pin. The objective is to have low friction and a minimum of wobbling.

Step 3: Using the principles in Table 2, it is seen that the design in Figure 5A contains several ambiguities. The principles F,M,L,R,S are violated, meaning that the design is ambiguous. In Figure 5-a it is seen that interface element 'a' constrains the X- and Y-directions. Element 'b' constrains the Z-direction. However, both a and b constrain RX and RY (M-principle). The round and flash at the bottom of the shaft can affect component placement (F,R). An infinitely small change of the angle of the bottom surface of the gearwheel can abruptly change the contact point between the gearwheel and the shaft (Figures 5b/c), hence changing the friction significantly (S). The large contact surface between the shaft and the gearwheel puts demands on form tolerances (L), otherwise the gearwheel may 'wobble' during operation (Figure 5d), thereby creating noise. In Figure 5e, a design is proposed, which is very close to ideal Design Clarity. The Design Ambiguity has gone from 11 to 0.

Step 4 – List functional requirements.

1. Minimum rotational friction (because friction reduces gear efficiency)
2. Minimum wobbling around X- & Y-axes. Wobbling contributes to noise from the gear.

Step 5 – List design parameters.

Now, it is more clear which design parameters influence the functional performance and hence, traditional Robust Design Methods can now be introduced, optimising the parameters of the design. Also, tolerance and structural analyses will benefit from the improved design clarity.

Case 2: Pin Assembly

This case is based on an interface often seen in industrial applications – see Figure 6.

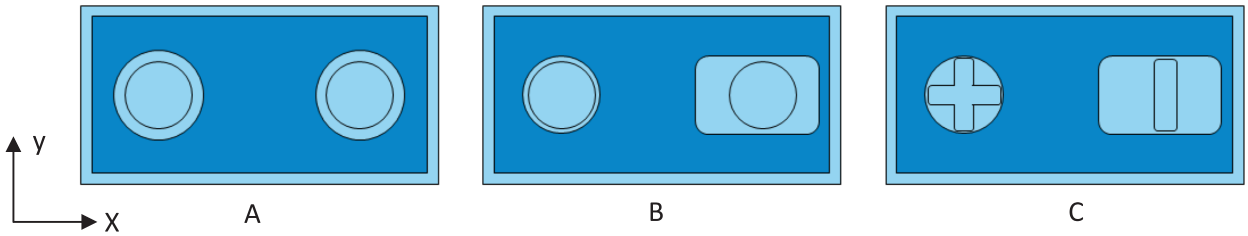


Figure 6 – Interface between a component with two pins and a component with two holes. All 6 DOFs are to be constrained. In A) the design is ambiguous. In B) the design is improved. In C) the design has been further optimised for robustness, thereby reducing the variance of the holding force.

Using the step-by-step procedure:

Step 1 – Identify interfaces. There are only two parts, and they interface with each other.
Step 2 – Intended DOFs. The two components should act as a single body, i.e. all 6 DOFs are intended to be constrained.

Intended Degrees of Freedom		
X	Y	Z
0	0	0
RX	RY	RZ
0	0	0
0 = constrained, 1 = free, -1 = overconstrained		

Actual Degrees of Freedom		
X	Y	Z
-1	-1	0
RX	RY	RZ
0	0	0
0 = constrained, 1 = free, -1 = overconstrained		

Step 3 – Principles of clarity
In Figure 6-a it is seen that both pins control the X- and Y-directions (M-principle). The remaining constraints are as intended (it can be argued that RX and RY are overconstrained but here the length of the interface between the pins and the holes is assumed to be so short that the interface does not control RX and RY. In Figure 6-b an alternative design is suggested, with the left pin controlling X and Y and the right pin controlling only RZ. Using the same tolerances, it is now possible to create a closer fit between the pins and holes.
Step 4 – List functional requirements.

1. Position tolerance of component placement
2. Stress level in components lower then tensile stress

Step 5 – List design parameters.
Having reduced the size of the interface elements of the pressfit, it will be possible to design with a larger overlap between the two parts, without exceeding the allowable stress levels of the materials. Due to the larger overlap, the influence of the tolerances wrt. the holding force will be redueced and thus the design is more robust.

7. Conclusions

In this paper, a review of literature has shown that there is a lack of specific and operational methods and tools for early-stage synthesis of robust designs. However, it is also shown that Kinematic Designs and designs with high Design Clarity are more robust against variations in design parameters than a corresponding design which is overconstrained and ambiguous.
During concept design, it is suggested to use the Kutzbach-Gruebler formula to secure that the mobility of the concept is as intended, as overconstrained designs can lead to parasitic loads and variation in product lifetime, noise, vibrations and unwanted deflections.

During the interface design phase, a step-by-step method is proposed for systematically analysing all interfaces and identifying any ambiguities. This is done using the specific set of Clarity Principles. Failure to remove ambiguities in the design can lead to component misplacements, lack of precision in tolerance and structural analyses and abrupt functional changes, which again can result in variation in functional performance.
When attempts have been made to obtain a kinematically correct and unambiguous design, traditional Robust Design Methods can be implemented, focusing on further optimising the design parameters wrt. robustness.

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Abstract

This constribution argues that prior to using traditional Robust Design Methods, it is essential that attempts have been made to obtain an ideally constrained and unambiguous design, which are both correlated with the robustness of a design. Two methods, Kinematic Design and Design Clarity are described, that quantify the mobility and ambiguity of a design in a simple way, allowing for the methods to be used during early-stage design where design iterations are fast and hence do not allow for more elaborate methods.

9.3 Paper C

"Robust Design Principles for Reducing Variation in Functional Performance"

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Robust design principles for reducing variation in functional performance

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ABSTRACT
This paper identifies, describes and classifies a comprehensive collection of variation reduction principles (VRP) that can be used to increase the robustness of a product and reduce its variation in functional performance. Performance variation has a negative effect on the reliability and perceived quality of a product and efforts should be made to minimise it. The design principles are identified by a systematic decomposition of the Taguchi Transfer Function in combination with the use of existing literature and the authors' experience. The paper presents 15 principles and describes their advantages and disadvantages along with example cases. Subsequently, the principles are classified based on their applicability in the various development and production stages. The VRP are to be added to existing robust design methodologies, helping the designer to think beyond robust design tool and method application, towards forming product variation management strategies.

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KEYWORDS
Robust design; design strategies; quality management

1. Introduction

The quality of a product lies in its ability to consistently meet user expectations in terms of its functional features and its behaviour. Examples of functional behaviour could be the force required to open a car door or the noise generated by a motorised TV wall bracket. The inevitable presence of variation in the properties of the product's components, caused by, for example, conditions of use and variation in manufacturing and assembly, results in variation in the functional behaviour of the product. The variation can occur either over time within the same sample or as variation from sample to sample. The variation conflicts with the intention of consistent behaviour and can lead to product failures, dissatisfied customers, the need for increased quality control, and added development and service costs – all of which impact the overall profit of the organisation (Ebro, Krogstie, and Howard 2015). Therefore, it should be the aim of the design engineer to design the product and define relevant subsequent activities such that the variation in functional behaviour is minimised. A product typically has multiple functions and sub-functions, which can be *identified* and *mapped* using, for example, Functions/Means Trees that decompose the product's main functions into sub-functions, or quality function deployment (QFD) that creates links from qualitative customer statements (Voice of the Customer) to functional requirements and design parameters. Multiple

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methods and tools are available for *analysing* the level and the effects of variation in functional behaviour of a design, for example, design of experiments (DOE), variation mode and effects analysis (VMEA) and failure modes and effects analysis (FMEA). Although these methods identify potential failure modes and sensitive design parameters, they only provide limited guidance as to how the variation in performance can be *reduced*. This paper seeks to present a comprehensive collection of design principles that can support the design engineer in selecting the most appropriate principles for reducing variation in functional behaviour, thereby answering the question:

> Which principles are available for reducing variation in the functional behaviour of a product?

The focus of the variation reduction principles (VRP) is *not* delimited to the design of the product, but also includes principles related to, how the product is produced and assembled, thereby resulting in a wider range of principles.

The remainder of the paper consists of six sections: Section 2 – theoretical background; Section 3 – methodology, describing how the principles have been identified; Section 4 – a presentation of the VRP; Section 5 – a categorisation of the principles; Section 6 – discussion of the value, limitations and intended use of the VRP; Section 7 – conclusion, which summarises the paper.

2. Theoretical background

This section first describes the theoretical background of why it is beneficial to obtain products with a low variation in functional performance and then describes current frameworks of principles, practices and tools for obtaining consistent performance.

2.1. The need for consistent behaviour

A product is defined by its structure, which describes the characteristics of the product and by its behaviour, which describes how the product performs (Andreasen, Howard, and Bruun 2014). The intended behaviour of a product is described by the product specifications, typically using a target value and an upper and/or lower acceptance limit, for example, 'Force to trigger dose button = 7 ± 1N'. Initially, only high-level specifications are defined, but during the course of the development project, a substantial number of additional functional requirements may be added as sub-functions and design details are included in the design, for example, the required holding force of a screw connection. The design engineer is faced with many requirements in terms of cost, risk, quality, reliability, robustness, etc. Amongst these requirements is the task of obtaining a design where all functional specifications are fulfilled. This involves two different types of activities: (1) nominal dimensioning, where the product's design parameters are defined (dimensions, material properties and surfaces (Tjalve 1976)), striving to obtain a nominal performance equal to the target specification. (2) Minimising the variation in functional performance. Because the world is stochastic by nature, variation will occur in the product's design parameters and this will lead to variation in the functional performance, both within the same sample over time, for example, due to temperature changes and wear and from sample to sample due to, for example, wear of the production tools or float during assembly. A large variation in functional performance can have a negative influence on the design in several ways:

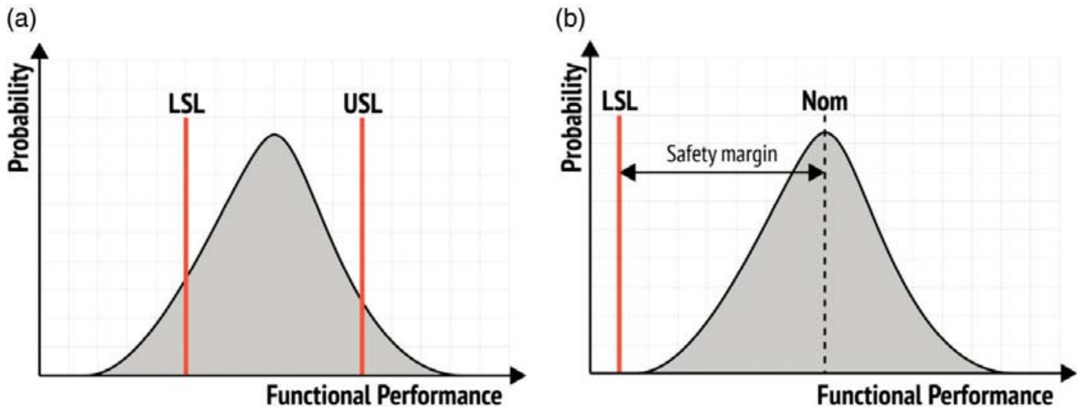

Figure 1. (a) Large variation in functional performance increases the probability of performing outside the upper and lower specification limits (USL and LSL). (b) Large functional variation results in the need for a larger safety margin.

(1) *Failures due to exceeding specification tolerance limits*: If the functional variation is high, it will increase the probability of products performing outside the defined specification limits, meaning that the failure rate will increase, as shown in Figure 1(a), where the variation must be reduced to fulfil the functional requirements. In other words, a large variation in functional performance can result in poor reliability.
(2) *Excessive cost due to increased safety margins*: For one-sided specifications (lower/higher-the-better) the objective is to minimise the expected failure rate by defining a sufficient safety margin between the nominal performance and the specification limit (Figure 1(b)). A design with large performance variation must have a larger safety margin to obtain the same probability of failure, which can lead to material waste, added cost, increase in the size of the product, etc.
(3) *Dissatisfied customers due to quality loss*: In the traditional understanding of quality, any performance within the performance specifications is perceived as being equally acceptable. However, the quality loss function (QLF) developed by Taguchi, Chowdhury, and Wu (2004) states that any deviation from the intended value incurs a loss to the user and the society, an example of which is given in a popular case study by Phadke (1995), where two TV-production sites adhering to the two different quality paradigms experienced large variations in customer satisfaction. As shown in Figure 2, when the variation in functional performance is reduced, the number of users experiencing a given (high) quality loss is also reduced. Quality loss can also occur internally in an organisation, for example, as problems with the assembly of a product, requiring it to be reworked, scrapped or taking extra time to assemble.

Summing up, reducing the variation in functional performance is an essential part of the design engineer's tasks as it has obvious links to the perceived quality, failure rate, reliability and profitability of the product.

2.2. Existing frameworks and compilations

The task of reducing variation in functional performance can be seen as an ongoing and iterative process consisting of three steps (Figure 3), each with a designated set of tools and methods.

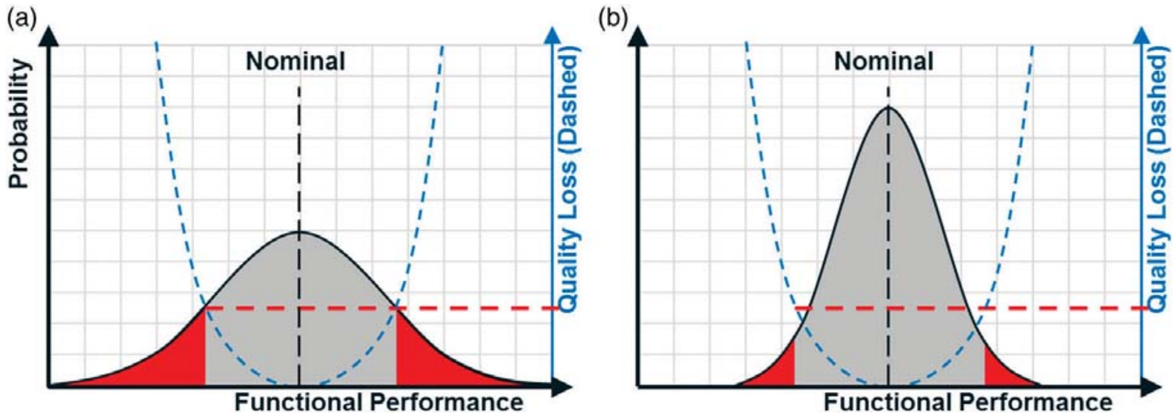

Figure 2. A design with a large variation in functional performance (a) will have a higher share of samples performing with a given quality loss (red area) compared to a design with a smaller variation in performance (b).

(1) *Identifying* functional requirements involves a continuous decomposition and mapping of functions and sub-functions along with the relevant performance requirements using methods such as QFD (Akao and King 1990) and Functions/Means Trees as well as frameworks like variation risk management (Thornton 2004) and the more general field of requirements management. The output of this step is a list of functional requirements, ideally with allowable variation limits.
(2) *Analysing* the design to identify the nominal as well as the variation in the functional performance. This is done using general tools such as tolerance calculations and structural analysis as well as more specialised tools such as FMEA (Teng and Ho 1996), VMEA (Chakhunashvili, Johansson, and Bergman 2004), DOE (Phadke 1989) and fault tree analysis (Lee et al. 1985) that describe the occurrence and effects of performance variation.
(3) *Designing* the product involves the definition of the product's structure (i.e. form, dimensions, material and surface), but the designer also plays a role in defining subsequent activities in manufacturing and assembly (Booker, Raines, and Swift 2001), for example, through tolerance requirements on the production drawings and testing procedures.

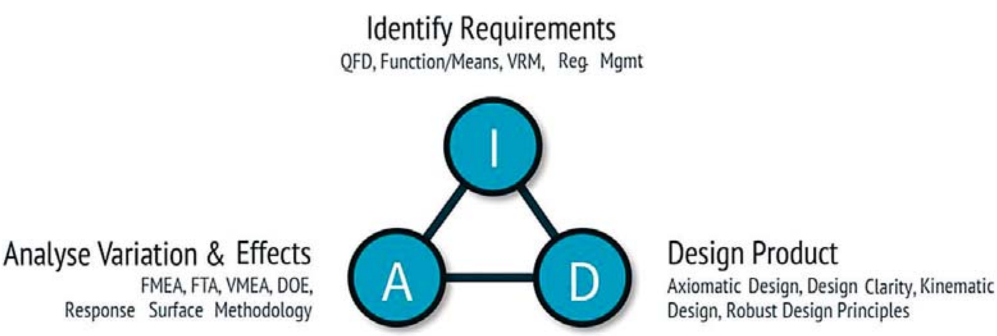

Figure 3. The iterative workflow related to variation in functional performance. The design engineer shifts between identifying requirements, analysing and documenting sensitivity and performance, and designing the product.

The design step, that is, identifying ways of reducing functional variation, is described in existing literature, which comprises a number of compilations and frameworks, some of which are listed below.

Matthiassen (1997) provides a set of specific design principles for obtaining robust and reliable designs, such as redundancy and the separation and integration of functions. The principles focus on the product itself and do not include principles applicable in production and assembly.

Thornton (2004) provides a framework for identifying a product's key characteristics, measuring the performance of the product and mitigation strategies for improving the performance. The mitigation strategies can be further extended and added to the ten design principles for reducing variation proposed by Andersson (1996), and to the principles of robust design proposed by Arvidsson and Gremyr (2008), although their main focus is on experimental and analytical tools and less on design principles.

Taguchi (1986) provides a three-step process (system, parameter and tolerance design) for eliminating variation. The main focus of this work lies on the parameter and tolerance design and the statistical optimisation of parameter values. As such, the focus is relatively narrow and does not include, for example, changing the design concept.

Design for six sigma (Yang and El-Haik 2003) is a framework which has gained popularity in recent years. The main driver is obtaining 'six sigma performance' by design (rather than by production only). The main focus is on the overall design process (Define, Measure, Analyse, Improve, Control) and less on the specific solutions and principles.

Finally, generic development processes, such as Pahl et al. (2007) typically provide various Design-for-X guidelines, such as design techniques for obtaining easy manufacturing, easy assembly and low cost. However a process that focuses specifically on eliminating performance variation has not been found.

The existing compilations and frameworks provide different types of overviews of tools, principles and methods related to quality engineering, and the reliability and robustness of a product. It is therefore argued that there is a potential for augmenting the existing compilations, by specifically targeting the variation in functional performance and by also including principles outside of the design domain. Especially principles that provide specific support for the design engineer and are applicable at the point-of-design are needed. Such an overview will complement the large suite of methods available for identifying functional requirements and analysing the performance of designs (as shown in Figure 3) and will compile and extend available design strategies by also covering strategies not directly related to the design of the product, but rather how the product is manufactured and assembled.

3. Research methodology

This section describes the methodology used to identify and structure the design strategies. The strategies have been identified using the Transfer Function as a structured framework. The Transfer Function (Figure 4) is a visual and mathematical representation of the relationship between the functional performance and the design parameters that affect the performance (Taguchi 1986). It consists of three main elements: (1) the design parameter(s) on the horizontal axis, (2) the sensitivity of the design shown by the graph and (3) the functional performance on the vertical axis.

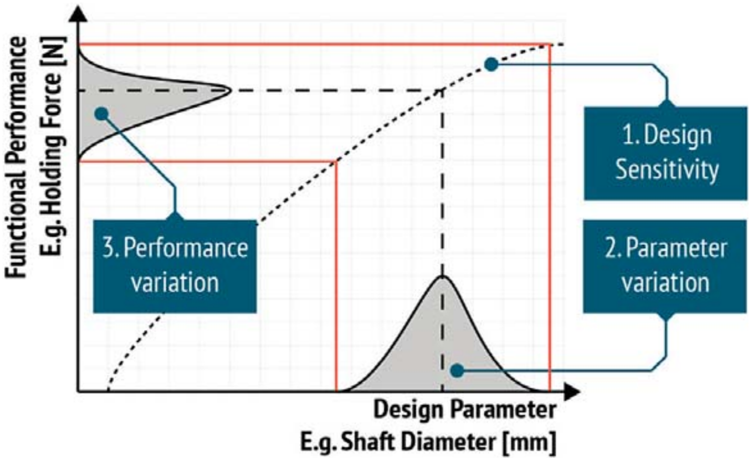

Figure 4. The Transfer Function's three main elements were used as a framework for identifying the variation reduction strategies.

Improving any of the three main elements of the Transfer Function will result in a reduction of the performance variation. For each of the three elements, strategies were identified by analysing relevant literature supplemented with the authors' experience as consultants and researchers within the fields of reliability, quality and robustness in engineering design.

For each of the identified strategies, the advantages and disadvantages were described and a relevant case was provided to illustrate the use of the strategy. Certain strategies are directly related to the design of the product, whereas others relate to the way the product is manufactured or assembled. To illustrate this, the strategies were mapped onto a generic product development process, thereby indicating at which phases the given strategies are applicable.

4. Design principles

This section presents the 15 VRP that have been identified. They are structured into three groups, based on which element of the Transfer Function they address. References are provided for the principles where further information is available in literature.

4.1. Principles related to design sensitivity (changing or shifting the Transfer Function)

1 – Parameter optimisation
Description: If the Transfer Function is non-linear, the performance variation can be reduced by adjusting the values of the design parameters to fit with the 'flat' (non-sensitive) areas of the transfer curve. *Example: Press fit* The holding force of a press fit is very sensitive to variation of the overlap between the two parts. The design is changed from a long interference fit (Figure 5(a)) with a small radial overlap, to two short fits with a larger overlap (Figure 5(b)). The nominal holding force is the same but the variation in holding force is reduced significantly.

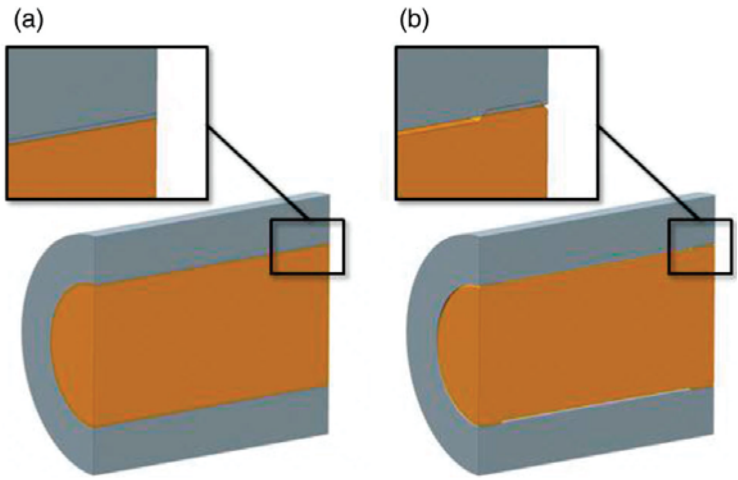

Figure 5.

Pros:
Parameter optimisations typically will not require any conceptual changes, which allows for this strategy to be applied relatively late in the design process.

Cons:
- Not all sensitivities can be found analytically, but require tests, simulations, DOE.
- Requires a non-linear Transfer Function.
- Limited improvement potential.

References: Taguchi (1986)

2 – Change of design principle

Description:
If the conceptual solution is changed, the Transfer Function and the design parameters will also change. As part of the concept selection process, the expected performance variation of each solution can be calculated and used as input.
Example: Wind turbine coupling
A coupling and bearing system for the main shaft of a wind turbine was designed to have a nominal lifetime of 20 years, but was very sensitive to misalignment of the bearings, with large variation in expected lifetime as a result. A conceptually different system was designed introducing several more degrees of freedom to the gearbox coupling. This made the design insensitive to misalignment, which extended the nominal lifetime and improved the predictability of the performance, which made predictive maintenance easier.

Pros:
Potential for larger improvements compared to, for example, parameter optimisation.

Cons:
By default, this strategy requires a complete change of concept.

References: Thornton (2004)

3 – Uncoupling and decoupling

Description:
If multiple functions depend on the same design parameter, the range of available values for a design parameter is reduced, because two functional requirements have to be met simultaneously. As a consequence, the design engineer may have to make a compromise and select design parameters resulting in a mean functional performance that is different from the target value, which in turn increases the performance variation.
Example (*adapted from* Söderberg, Lindkvist, and Dahlström (2006)): *Positioning of parts*
The positions of components A–D have functional requirements. In a coupled design (Figure 6(a)), the position of, for example, D will depend upon the positions of A–C, which reduces the probability of finding an optimal solution for all four components. In the decoupled design (Figure 6(b)), the parts can be designed in a specific order, and thereby compensate for design parameters, that have been 'locked' by previous requirements. In the uncoupled design (Figure 6(c)), the designer is free to specify the optimum design parameters.

Pros:
Reduces number of trade-offs, as functional requirements can be optimised individually.

Cons:
Challenging to identify the coupled design parameters early in the design process, and challenging to decouple them late in the design process, especially for highly integrated products.

References: Söderberg, Lindkvist, and Dahlström (2006), Suh (2001)

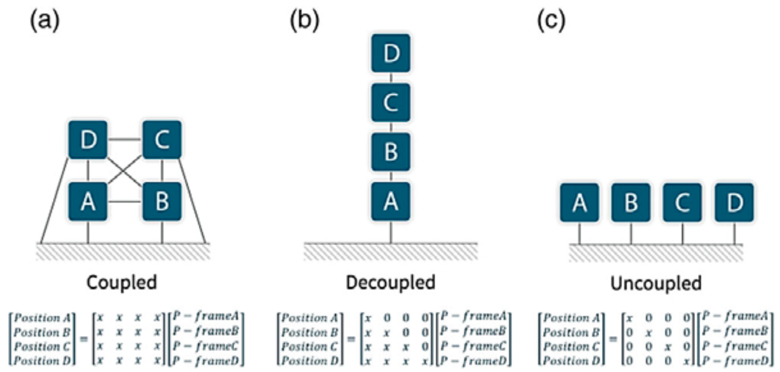

Figure 6.

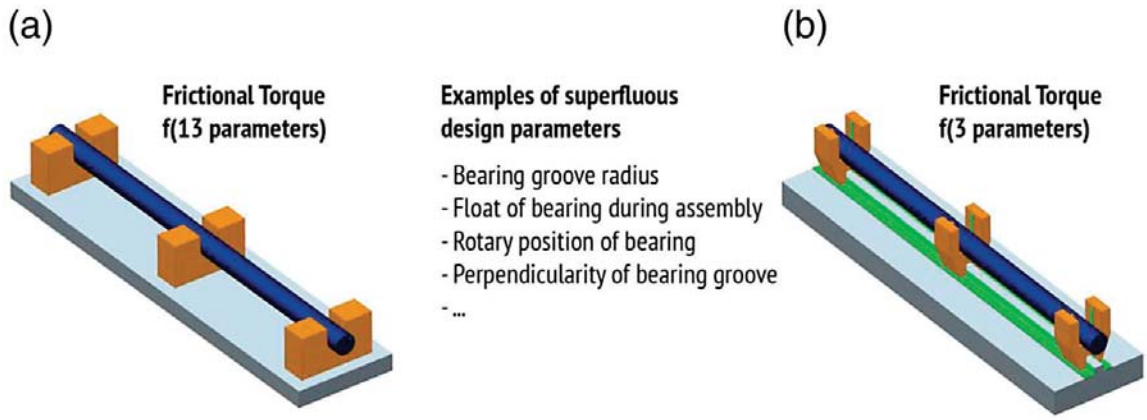

Figure 7.

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4 – Minimise number of design parameters (design clarity & kinematics)

Description:
Intuitively, the variation of a functional performance is proportional to the number of influencing design parameters, because the variation of each design parameter will contribute further to the variation of the functional performance. This strategy focuses on reducing the number of influential design parameters by using the principles of kinematics and design clarity. Avoiding long tolerance stack-ups is an inherent part of applying this strategy.
Example: Large flatbed scanner
A shaft for a large flatbed scanner has to run with constant frictional torque to produce high-quality scanning images. In the original design (Figure 7(a)), the torque was a function of 13 design parameters, due to over-constraints and interface ambiguities. In the new design (Figure 7(b)), the number of influencing parameters is reduced to three, resulting in reduced variation in frictional torque.

Pros:
- Reduces the number of specifications, resulting in a reduced need for verification and quality control
- Often, changes to the detailed interface design are sufficient.

Cons:
Conceptual changes may be necessary in certain situations.

References: Blanding (1992), Christensen, Howard, and Rasmussen (2012)

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5 – Self-reinforcement

Description:
This principle is an extreme case of sensitivity reduction, where the functional performance improves as certain design parameters deviate from nominal conditions.
Figure 8
Example: Rubber seals
One functional requirement of a sealing is that it must not leak. If the pressure difference becomes too high, a solution with an o-ring will leak. A lip-ring, however, becomes tighter as the pressure increases. Hence, the functional performance is independent of the pressure.

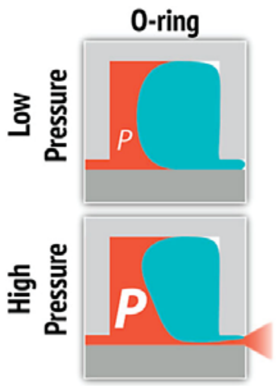

Figure 8.

Pros:
Functional variation is eliminated even for extreme parameter variation.

Cons:
- Not generally applicable.
- Typically, the reinforcement only works in one direction.

References: Matthiassen (1997)

6 – Flexibility

Description:
Flexible parts can absorb parameter variation and therefore reduce the performance variation. It is worth noting that flexibility is a function of both material properties and geometry, and changing either of these will change the functional performance. This strategy is especially applicable for functional requirements involving load-bearing parts.
Examples: Chair and LEGO®-brick
One functional requirement for a LEGO®-brick (Figure 9(a)) is the 'clutch power' (the force to assemble and disassemble the bricks) which should be within a narrow range for billions of combinations of bricks. By combing a flexible material (Acrylonitrile butadiene styrene) with a geometry where only limited volumes of material have to be deflected in the press-fits between the bricks, the variation in the clutch power is reduced. Figure 9(b) shows how the interface features consist of tiny protrusions and small ribs that act as deformation zones. Figure 9(c) shows the geometry (red circle) of the interfacing LEGO®-brick

Pros:
Can be executed as a material selection and/or a design change

Cons:
- Permanent stress in parts, which could lead to creep.
- Position accuracy and predictability of parts is reduced
- Flexible parts can experience large deflections, which may not be desirable.

References: Andersson (1997), Christensen, Howard, and Rasmussen (2012)

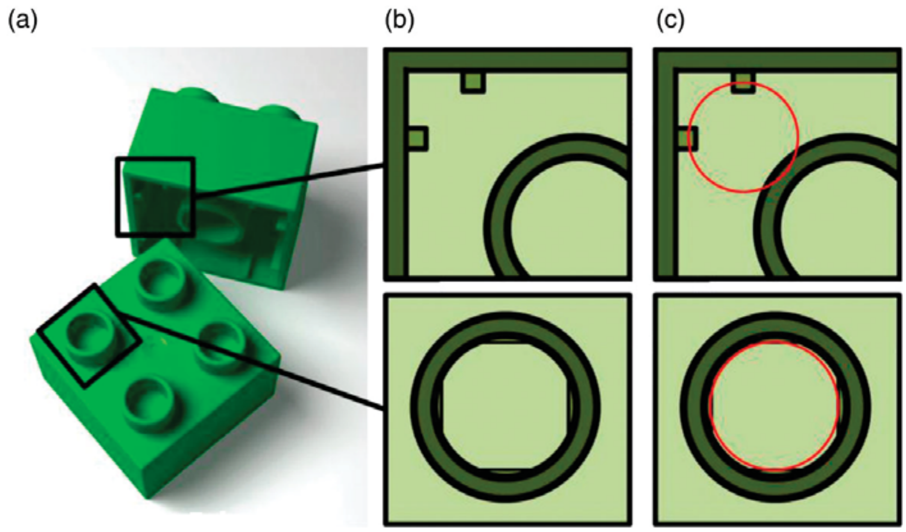

Figure 9.

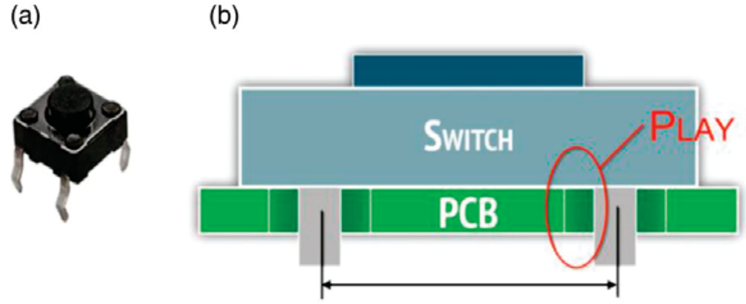

Figure 10.

7 – Play

Description:
Introducing play essentially 'delays' how variation of a design parameter influences the functional performance. If play exists between two functional surfaces, variation of one surface can occur to some extent without affecting the interfacing surface (depending on the specific design) and therefore will not change the functional performance.
Example: Electromechanical switch
One functional requirement for a push-button switch is the allowable stress on its terminals, when it is mounted on a printed circuit board (PCB). Variation in the distance between the holes of the PCB will result in stress in the terminals of the switch when it is mounted. By introducing play (larger holes), the design becomes less sensitive to variation in the hole distance, which in turn results in the stress in the terminals being eliminated within a certain variation window.
Figure 10

Pros:
Applicable at detailed design stage.

Cons:
- The positioning accuracy in the interface is reduced, because the float or assembly variation will be increased.
- Play can lead to noise/rattle due to vibrations and feel sluggish to the user.

References: N/A

8 – Redundancy

Description:
Redundancy is typically used where the functional variation can become so extensive that it turns into a failure with serious consequences. The redundant functionality can be inactive during normal use, for example, a back-up power supply for a nuclear power plant, or be an active part of normal use, for example, multiple engines on an airplane.
Example: Coaxial piping
One functional requirement of a pipe for transporting, for example, liquids is to prevent leakage. Due to, for example, corrosion, a pipe can lose containment (leak). However, if a coaxial system of pipes is used, the outer pipe is initially redundant, but becomes active when the walls of the inner pipe become corroded.
Figure 11

Pros:
- Avoidance of serious effects of failure.
- Allows for safe detection of need for maintenance.

Cons:
- Conceptual decision – difficult to implement at the detailed design stage.
- Added cost of a redundant system.

References: Matthiassen (1997)

4.2. Principles related to parameter variation

9 – Tight tolerances

Description:
Tightening the allowable parameter variation will inherently reduce the performance variation, especially if this is targeted at the design parameters that have the largest influence on the functional performance. These parameters can be identified using sensitivity studies.

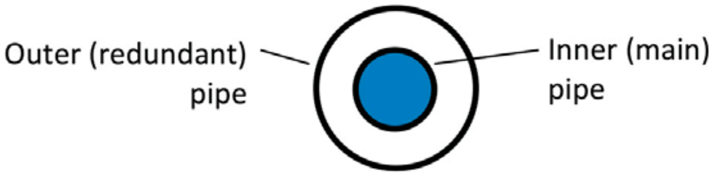

Figure 11.

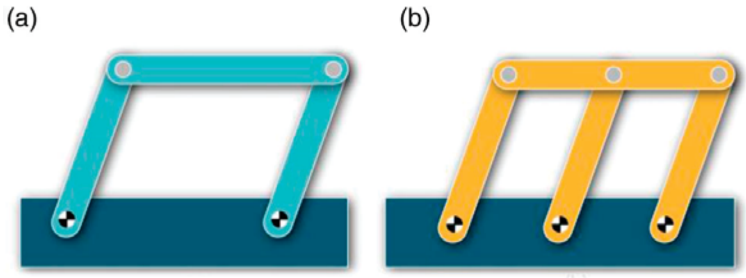

Figure 12.

Example: An overconstrained mechanism
A mechanism should ideally have a mobility equal to the number of motion inputs to the system (a), otherwise it may jam. However, theoretically overconstrained mechanisms (b) can still work, if the variation of the design parameters is low, for example, if the lengths of the links and positions of the joints are precise.
Figure 12

Pros:	*Cons:*
Only requires changes on the production drawing, and therefore very simple to apply at late design stages.	• Tightening tolerances increases cost (higher scrap rates, extra machining processes, added quality control, etc. • Risk of tightening tolerances beyond the process capability. • Variation from loads, ambient conditions and wear cannot be controlled by this strategy.

References: Taguchi, Chowdhury, and Wu (2004)

10 – Sorting and matching during assembly

Description:
During assembly components can be sorted and matched to fulfil the functional requirement, for example, an intended fit or stack-up height of components. Essentially, parts are categorised based on the values of given design parameters and then paired with the appropriate category of the interfacing part.
Example: iPhone 5
One functional requirement on the iPhone 5 is the size of the split line on the backside (left). To fulfil the requirement, the frame is scanned and paired with the best match amongst 725 possible plates (right) that have also been scanned. This is done automatically using assembly robots and vision technology.
Figure 13

Pros:	*Cons:*
Extremely tight fits and split lines made possible with looser tolerances.	• Extra process step → Longer assembly time. • Replacement/service of parts can be difficult, since spare parts may not fit. • Quality is operator dependent (if done manually). • Risk of scrap if the distributions of the different components do not match each other (many small ‘holes’, but only a few small ‘pins’).

References: Thornton (2004)

11 – Shielding

Description:
This strategy reduces parameter variation by shielding the product from the cause of the variation. Thermal expansion can, for example, be avoided by insulating critical components and deflections from loads can be avoided by designing the load path so sensitive parts do not experience any loads.

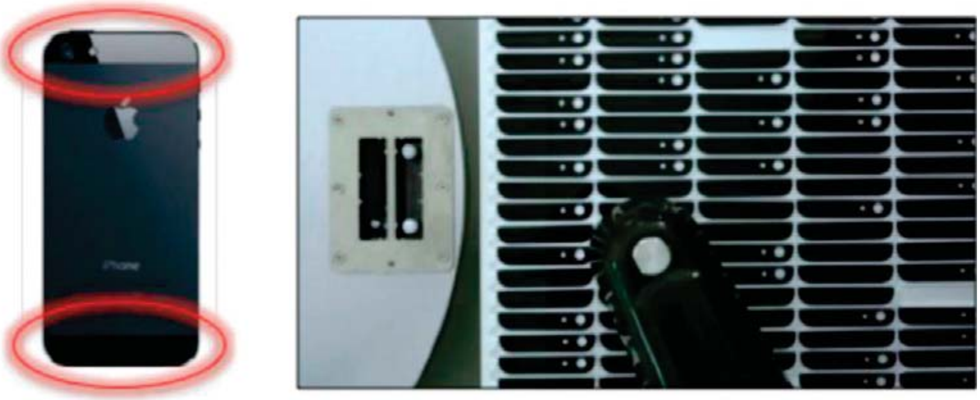

Figure 13.

Example: Space shuttle thermal protection tiles
The tiles used for thermal protection of the NASA space shuttles during re-entry in the Earth's atmosphere are very brittle and cannot withstand the structural deflections and expansions of the shuttle itself. Therefore, they are shielded from deflection by being glued to a separate Strain Isolation Pad, which in turn is glued to the shuttle.
Figure 14

Pros:
Noise factors such as temperature and loads are difficult to predict and specify. Shielding can reduce the need for use specifications.

Cons:
Primarily relevant for cases involving thermal variation and loads.

References: N/A

4.3. Principles related to performance variation

12 – Adjustment during assembly and in use

Description:
A product can be designed to allow for adjustment during assembly and in use. In practice, a given functional performance is measured and specific adjustments are made, until the functional performance is as intended. This can be done by using grub screws, clamping, shimming, spacing, etc. The adjustment can be carried out during manufacturing, during assembly, prior to use and during use.
Example: Motorised wall bracket for TV
One functional requirement of a TV wall bracket is the angular deviation of the TV from a perfect horizontal line. Since the designers have no control of how close to horizontal the bracket is mounted on the wall, an adjustment screw (red circle) is added to the bracket to enable the user to adjust the TV after it has been mounted. When noise factors (uncontrollable to the designer) enter during the user installation or use phases, enabling user adjustment is often necessary.
Figure 15

Pros:
- Compensates for noise factors and parameter variation over time and during use.
- Allows for more parameter variation (looser tolerances) during production, because these are eliminated by the adjustment.

Cons:
- Assembly time is longer, due to time spent on adjustment.
- Quality can depend on the competencies of the operator/user

References: Thornton (2004)

13 – Post-assembly processing

Description:
This strategy is based on processing certain features *after* assembly of the relevant parts, thereby reducing the parameter variation.
Example: Chair

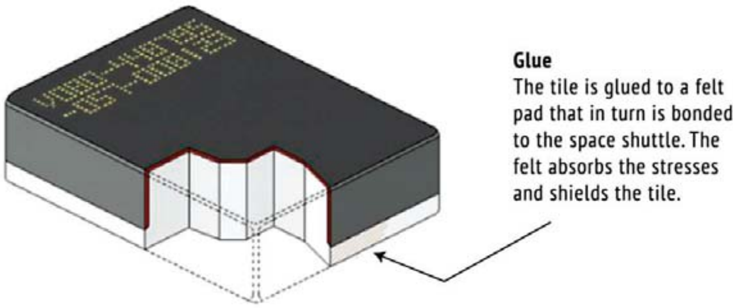

Figure 14.

Large complex carbon fibre shells with high levels of variation make drilling holes prior to and aligning during assembly unfeasible. Instead, mounting holes are drilled *in-situ* after the shells have been assembled. This ensures that the holes are correctly aligned. However, it does not ensure that they are positioned the same for each product and exchanging parts (e.g. in case of service replacements) is not possible.
Figure 16

Pros:
Reduced need for precision and control of design parameters.

Cons:
- Extra process step.
- Risk of compromising the sub-assembly during processing.

References: N/A

14 – Quality control

Description:
Parts and products can be subjected to in-line quality control during and after assembly. This strategy will keep sub-assemblies and products with a performance deviating too far from the intended value from reaching the market. The products that are taken aside can either be scrapped or re-worked. The earlier in the assembly process the quality control takes place, the lower the cost of scrap will be.
Example: Medical device
Quality control is used heavily in the medical device industry. During the automated assembly of an injection device, each assembly station is succeeded by a control station, which controls the performance of the sub-assembly. Examples include vision control equipment that controls the position of the print on the housing and depth gauges that control the position of an assembled part. Sub-assemblies not fulfilling specifications are scrapped – therefore the drug cartridge – which is by far the most expensive component – is assembled last.

Figure 15.

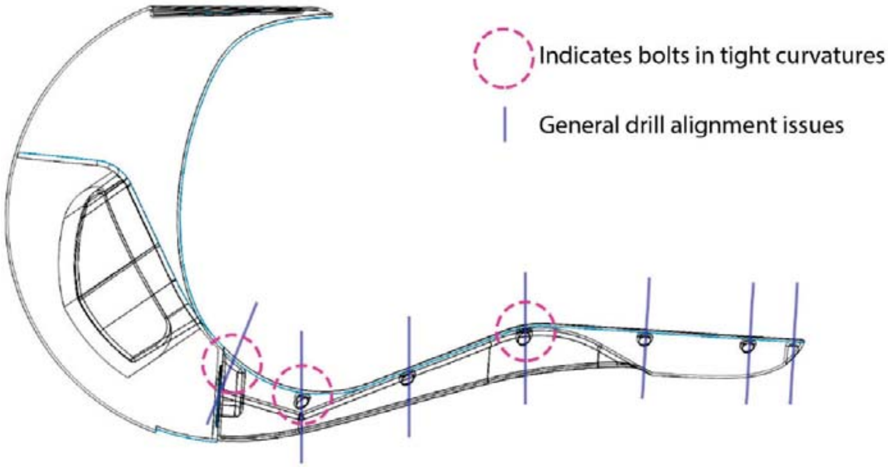

Figure 16.

Pros:

- High level of control of what reaches the market
- Costs of in-line control equipment using, for example, vision technology is steadily decreasing.

Cons:

- Requires control of all products which can be costly.
- Scrap rates can become excessive, leading to high costs.
- Not actually *reducing* variation, but merely removing products not performing as intended.

References: Booker, Raines, and Swift (2001)

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15 – Change functional requirements

Description:
In certain cases, the reliability of the functional requirements can be challenged. If the gradient of the QLF is low, the quality loss associated with deviating from the nominal value is limited and therefore it may be a more viable strategy to change the specifications than to change the design of the product.
Example: Motorised TV wall bracket
The initial requirement for the horizontal misalignment of a TV wall bracket was 0.5°, which was challenging to fulfil. A mock-up test documented that the users did not notice a misalignment until it exceeded 1.5°. Therefore, the functional requirement was changed.

Pros:
Does not require any changes to the product.

Cons:

- From the user's point of view the quality of the product has not improved.

References: N/A

5. Categorisation

In this section, the identified principles are categorised. It is our impression that the cost and benefit of applying a given principle will depend so much on the specific context that it is not possible to quantify or rank the principles in terms of the cost of applying them. In general terms however, principles involving extra operations (e.g. sorting, matching and controlling) are expected to be less favourable than the principles based on a design change, because a design change is a one-off operation, whereas extra operations must be withheld for the remainder of the product lifetime, which is more costly.

An initial categorisation already exists, as the principles were identified using the three elements of the Transfer Function. Therefore, the principles have been grouped into the

Table 1. Applicability of VRP.

Category	Principles	Conceptual design	Embodiment design	Detailed design	Manufacturing	Assembly
Design sensitivity	1 – Parameter Optimisation		x	x		
	2 – Change of design principle	x	x			
	3 – Uncoupling & decoupling	x				
	4 – Minimise number of design parameters		x	x		
	5 – Self-reinforcement	x	x			
	6 – Flexibility	x	x	x		
	7 – Play		x	x		
	8 – Redundancy	x	x			
Parameter Variation	9 – Tight tolerances		x	x	x	
	10 – Sorting and matching during assembly	x	x	x	x	
	11 – Shielding	x	x			
Performance Variation	12 – Adjustment during assembly and use	x	x	x	x	x
	13 – Post-assembly processing	x	x	x	x	
	14 – Quality control	x	x	x	x	
	15 – Change functional requirements	x	x	x	x	x

categories of (1) design sensitivity, (2) parameter variation and (3) performance variation. Furthermore, it is of interest to categorise the principles in terms of when in the design process they can be applied. This is important because the number of potentially applicable principles is expected to decrease as the development project progresses. In Table 1, the VRP are mapped on a generic product development process model adapted from Pahl et al. (2007). Not surprisingly, the table shows that as a project progresses, the number of applicable principles is reduced and that once the manufacturing phase is started, only a limited and seemingly more costly selection of principles is applicable.

It is important to note that even principles related to later phases of manufacture and assembly should be decided upon during the early design phases when forming the product's variation management strategy.

6. Discussion

In this section, the intended use scenario, value, limitations and further research possibilities are discussed.

The VRP are intended to serve as a catalogue of inspiration for the design engineer and project management. It is the task of the design engineer to estimate, simulate or test the product's functional performance – not only in terms of the expected nominal performance, but also in terms of the variation in performance. There will always be a potential for further reducing the variation and ultimately the design engineer will have to make a trade-off between the costs of further variation reduction efforts, versus the loss incurred by the expected variation. Furthermore, the alternative to a design with high performance variation could be a design with less variation but with a nominal performance which is worse. This would also demand a trade-off by the design engineer. It is worth noting that the principles are not mutually exclusive, meaning that it is possible to combine multiple principles to obtain the desired results. Finally, it should be mentioned that the principles are not applicable in all design phases. As shown in Table 1, the design principles have a given 'window' where they are applicable. As an example, the principle 'Minimise number of design parameters' cannot be applied in the concept stage, as the design parameters have not been designed yet, but also cannot be applied during manufacturing (or later) as the design is then locked. These restrictions therefore dictate which principles should be considered in a given development phase.

The *value* of the VRP lies in their simplicity and early-stage applicability. The field of robust design and reliability has a tendency to primarily focus on late-stage analysis and verification and less on simple principles and strategies which are applicable at the *point-of-design*, that is, while the sketches and 3D-CAD are being produced. Furthermore, the value lies in the structure and comprehensiveness of the principles; they provide an overview of a wide array of alternative principles, which may support the design engineer in making the right decisions and pursuing all competitive principles for reducing variation in functional performance.

Although the advantages and disadvantages for each principle are presented, one of the *limitations* of the VRP is that it does not provide specific values for the costs and effects of applying a given principle. As a consequence, assumptions or further analyses must be made in order to evaluate whether there is a positive return of investment for applying a given principle.

As for *further research*, it would be interesting to analyse current industrial use of the presented principles and identify if and why certain principles are used more often than others, for example, due to certain principles being inherently better than others or due to when in the design process the principles are applied. Furthermore, a more detailed and more quantified description of the pros and cons for each principle would provide the design engineer with a better foundation for making the right decisions and trade-offs. Finally, a framework to capture where variation enters the product and where strategies can be targeted would help to define a more formal and rigorous approach to a product variation management strategy.

7. Conclusion

The aim of this paper was to identify principles for reducing variation in the functional behaviour of a product. Reducing the variation in functional performance is important because it reduces the product's failure rate, it prevents unnecessary over-dimensioning of parts and it reduces the quality loss experienced by the user. A catalogue of 15 design principles – called VRP – has been presented, along with case examples and a description of the advantages and disadvantages for each. Finally, the principles have been structured based on their applicability in the various product development stages. The VRP catalogue is intended to be a detailed support for the design engineer and a reminder to continuously strive for minimal variation in functional performance. Also, the VRP are seen as a counterweight to the many analysis and documentation tools often seen in the field of robustness and reliability engineering, as they are intended to be applied – or at least decided upon – at the point-of-design, rather than later in the design process.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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9.4 Paper D

”How to Implement and Apply Robust Design: Insights from Industrial Practice”
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How to implement and apply robust design: insights from industrial practice

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Robust design (RD) is a framework for designing products and processes which perform consistently in spite of variations. Although it is well described in literature, research shows limited industrial application. The purpose of this paper is to describe and discuss industrial best-practice on RD. Empirical findings are based on a series of semi-structured interviews with four major engineering companies in Northern Europe. We present why they were motivated to use RD, how it has been implemented and currently applied. Success factors for solving implementation challenges are also presented and the experienced effects of adopting it are described. The key findings are: (1) Training, roles, and responsibilities: All companies have given substantial training to their engineers and have implemented new roles with technical responsibility, (2) RD implementation is context dependent: The four case companies have all been successful in using RD but with quite different approaches, depending on, for example, their organisational culture, and (3) Not just management commitment, but also *true* management competencies in RD are essential for a successful implementation. The paper is aimed at professionals and researchers within the field of engineering design, considering why, if, and how to implement and apply RD in an organisation.

Keywords: robust design; product development; industrial practice; management strategy; success factors; variation; tolerances; implementation

1. Introduction

The purpose of applying Robust Design (RD) is to reduce the unwanted variation in the functional performance in a product and processes by designing it to be insensitive to various sources of noise. Insufficient robustness can cause lack of functionality, reduced product lifetime, and variation in performance as a result of noise, wear, and deterioration. Robustness can, therefore, be expressed as the product's ability to *consistently meet customer requirements*. Surveys show (Gremyr, Arvidsson, & Johansson, 2003; Thornton, Donnelly, and Ertan, 2000) that the majority of companies consider it to be 'important' that their products operate with low variation in functional performance. However, the same studies also show that only a limited number of these companies actually apply RD. An analysis of the industrial applicability of RD methods by Eifler, Ebro, and Howard (2013) showed that the majority of methods were not applicable during the early design stages, where decisions regarding the product concept and architecture are made. Furthermore, Thornton (2004) argues that '*the tools are not being routinely used*

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in industry because they are too complex and the data needed to populate the analyses is not available.' However, some companies have overcome the technical and organisational challenges of applying RD as part of their product development process. In detail, the purpose of this paper is to analyse these companies now experiencing the positive effects of RD in order to identify their (1) motivation to work with RD, (2) implementation strategies for tools, methods, training, metrics etc., (3) the corresponding barriers to this process, (4) the success factors solving those, and (5) the experienced effects of applying RD.

Existing RD literature has focused mainly on the development and description of new methods but has hardly considered the challenging task of communicating and implementing the methods in industry. We aim to provide a list of *solutions and results* already successfully applied in companies from different industrial segments and countries.

Further content is structured as follows. *Theoretical Background* handles perspectives on RD and challenges of implementation. *Methodology* justifies research methodology and case company selection. In *results*, the companies' practice and experiences on RD are described and archetypes of applying RD are *discussed*. The *Conclusion* presents best-practice recommendations for implementing and applying RD.

2. Theoretical background

In order to describe how the four companies have applied RD, we first provide a theoretical background that can be used as a framework for analysis and classification. Implementation of RD in an organisation is not just about the actual tools and methods, but also involves application of design methods and change management. Therefore, we also include a section on change management and organisational implementation of design methods.

2.1. *Traditional understanding of RD*

The traditional understanding of robustness and RD evolves in parallel from both a pragmatic engineering school represented by Taguchi (1986) and a statistical school by Box and Wilson (1951). Different perspectives and controversies were discussed by Nair et al. (1992). Typical differences in their goals on RD application have been in obtaining a 'working solution' and an 'optimal solution', respectively (Goh, 1993). Altogether, both schools have, to a large extent, focused on refining the methods of optimising different systems on their insensitivity to variation (aka noise).

Challenges in teaching and applying RD methods were addressed in the 1980s and 1990s (Myers, Khuri, & Carter, 1989), and more recent reviews (Myers, Montgomery, Vining, Borror, & Kowalski, 2004) continue to suggest extended research in technical areas as opposed to its industrial adoption which is also seen in Park, Lee, Lee, and Hwang (2006) and Murphy, Tsui, and Allen (2005). A review by Beyer and Sendhoff (2007) leaves the 'competition between the schools' aside and concludes '*Looking for synergies between the different philosophies in these fields is one promising approach towards a qualitative step in robust optimization*'.

2.2. *Emerging understanding of RD*

A more recent, pragmatic understanding of RD has been presented by Matthiassen (1997) proposing *RD principles* that would lead to more robust and reliable designs. This continued with Arvidsson and Gremyr (2008) explaining how Robust Design Methodology (RDM) is *more* than tools and methods and thereby define it to be '*systematic efforts to achieve insensitivity to noise factors*'. This definition supports the need for a more practical approach on RDM as research has shown several industrial challenges in applying RDM (Gremyr et al., 2003) and its surrounding statistical tools (Bergquist & Albing, 2006). Novel research approaches on RDM (Gremyr, 2005) and suggestions on how to operationalise it (Arvidsson, Gremyr, & Hasenkamp, 2006) have contributed to demystifying RDM towards an extended audience, and novel approaches (Johannesson et al., 2013) are gradually complementing existing tools. Proposals have been made on how to integrate RDM in a generic product development process (Hasenkamp, Adler, Carlsson, & Arvidsson, 2007; Thornton, 2004), some industrial insight on implementation is reported (Saitoh, Yoshizawa, Tatebayashi, & Doi, 2003a; Saitoh, Yoshizawa, Tatebayashi, & Doi, 2003b), and research has searched for the practices ('what needs to be done') that join the RDM-principles with the specific tools (Hasenkamp, Arvidsson, & Gremyr, 2009). Hasenkamp et al. also concludes '*there is little support in the literature to date that focuses on the continuous application of RDM*'. Altogether Arvidsson and Gremyr (2008) define the principles of RDM as being based on (1) awareness on variation, (2) insensitivity to noise, (3) application of various methods, and (4) continuous application. An extension of RDM towards visual robustness by Forslund and Söderberg (2010) quantifies the effects of variation on users' product quality perception. A growing acceptance of applying RDM in industry is currently observed (Gremyr & Hasenkamp, 2011), recent published books address industrial needs (Bergman, de Mare, Svensson, & Loren, 2009; Arnèr, 2014), and remaining difficulties in applying RDM continuously have been met with specific countermeasures suitable for industry. One example is Mashhadi, Alänge, and Roos (2013) reporting how a learning alliance between industry and university increased the acceptance on learning and applying RDM in industry. Other approaches to integrating RDM are seen in Parsley, Dunford, York, and Yearworth (2013).

2.3. *Organisational change within product development*

The traditional explanation of product development as a linear and rational process has been supplemented by a more flexible and collaborative approach which has been reported in later years (Kreimeyer, Heymann, Lauer, & Lindemann, 2006). Yet product development remains a complex and context-specific activity and authors tend to emphasise a limited set of facets of Product Development in their research. The *collaborative* sides of product development have been researched by Poggenpohl (2004) and the designers have been claimed to be among the most important assets of an organisation (Frankenberger, Badke-Schaub, & Birkhofer, 1997). Others see some element of performance measurement and related *metrics* as needed for success (Robson, 2005) and even link it to a '*culture of high performance*' which has its own body of research (Pentland, 2012). Others also see product development-success to be dependent on a *formalised process* where different stage-gates need to be passed (Cooper & Kleinschmidt, 2007) or by applying a certain methodology (Lindemann, 2009), yet with adaptions to the context. Product Development-success is seen as dependent on an *integrated* workmode that depends either on creating flow (Reinertsen, 2009) or understanding the complex nature of Product Development (Kreimeyer & Lindemann, 2011). Organisational changes involving the implementation of new design methods can face barriers such as reported by Hicks et al. (2009).

Advice on how to implement initiatives in product development organisations does, however, exist. The literature shows how similar (yet clearly different) initiatives such as Six Sigma principles was brought upstream towards Product Development (Banduelas & Anthony, 2003) and how Design for Six Sigma (DFSS) can be implemented (Ericsson, Gustafsson, Lilliesköld, & Sörqvist, 2009). As statistical techniques are reported (Bergquist & Albing, 2006) to be hard to implement in organisations, quite specific guidelines are proposed to help practitioners apply the methods (Costa, Pires, & Ribeiro, 2006). Other research has even seen congruence between the critical success factors of Six Sigma and the antecedents of successful organisational change (Pinedo-Cuenca, Pablo Gonzalez, & Setijono, 2012). Research has also explored how management control impacts the creation of knowledge within Product Development (Richtnér & Åhlström, 2010). Recent research has also explored how soft and hard factors interact in the case of Total Quality Management (Calvo-Mora, Picón, Ruiz, & Cauzo, 2013).

3. Methodology

Although the uptake of RD in industry is limited, certain companies have successfully implemented it in their development process, which makes it interesting to analyse why and how they have done this. Here we present our approach on empirical data gathering and some central characteristics of the companies.

3.1. *Gathering empirical industrial data*

In order to gain rich and deep impressions of industrial practice on RD, we performed a descriptive case study, which represents a description of a past or ongoing phenomenon (Leonard-Barton, 1990) drawing on different sources of empirical data. This insight comes from four different well-established industrial companies in four different countries developing, manufacturing, and selling products for different market segments. One key criterion prior to the selection was that a large degree of both product development and manufacturing should be in-house, which excluded selecting pure product development companies or stand-alone manufacturing plants.

Company selection was done to gain a balanced picture of various engineering segments and different locations, and similar comparisons are found in Davis (2006). Three companies were approached through ongoing research projects on RD and related topics. One company was approached upon reported activities on RD (Mashhadi et al., 2013). It is not claimed that the four top-performing companies on RD have been selected, but based on years in research, industry, and consulting, the authors are confident that the selected companies can provide relevant insights into the implementation of RDM. Company names have been anonymised due to confidentiality agreements, and replaced with a generic name in this paper, but the titles of the interviewees, all regarded as company experts on RD, are shown in Figure 1. The companies represent the industrial fields of *med*ical device industry (MED), *def*ense (DEF), *aero*space (AERO), and *auto*motive (AUTO). The motivation was to gain an impression of whether RDM is applied differently in the companies, as well as their perceptions on the current content and the challenges and benefits of aiming for designing robust products.

Semi-structured interviews were applied as the means to gather the main set of empirical data. Interviews are accepted as being a strong source of data supporting a deep understanding of a given phenomenon (Yin, 2003). An interview guide designed by the researchers was sent out to the interviewee some days prior to the interview. The interview

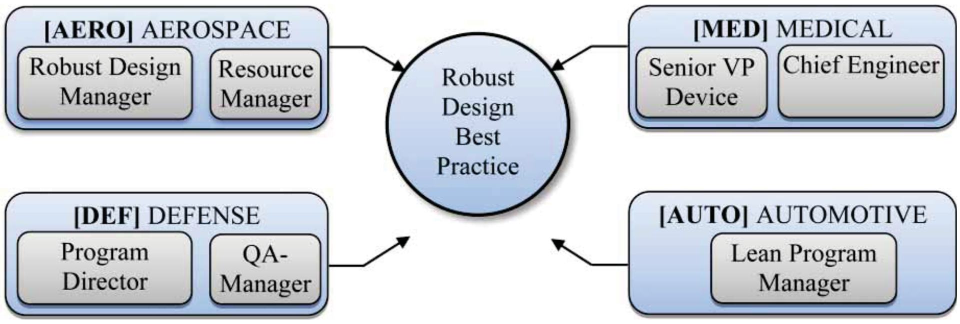

Figure 1. Interviews were carried out in four companies in four different countries in order to extract findings on RD best-practice.

questions revolved around the following core topics: (*Q1*) *Why* did you start applying RD (your concept of it/motivation for applying it), (*Q2*) *How* did you do it (starting point, current position, target for activities, organisation and implementation), (*Q3*) Challenges (*barriers* during implementation, application across department borders), (*Q4*) Counter-measures on challenges and its *success factors* to face the challenges, and (*Q5*) The *effects* of RD.

All interviews were kept within one hour in length, according to guidelines for qualitative research (Tjora, 2012), recorded digitally, transcribed, and coded after the interview. The approach of interviewing a small sample size of experts as opposed to surveying many novices is recommended by Lai, Lin, Yeh, and Wei (2006). No prescribed categories were used in the coding process and the RD-archetypes later identified arose from the data during coding and analysis. Research findings were discussed with the participating companies in separate sessions prior to publication.

3.2. *Case company characteristics*

MED is a Danish pharmaceutical company, which also develops and produces physical medical devices that the user can use to administer drugs. Production volumes of their devices are typically measured in ‘hundred millions per year’. Their production and assembly are spread across multiple lines in different locations around the globe. Users are highly dependent on the functionality of the devices, and they have to inject themselves up to several times a day. Injecting a wrong dose could have serious, and even lethal, consequences. The mechanical engineering department has several hundred employees.

DEF develops and manufactures rocket motors, aerospace, and ammunition systems and components. The company operates both in the military and civilian market segments. A large part of the development and manufacturing activities related to the researched activities of RD are located in Norway. Its typical products are characterised by high demands on reliability, product performance, and precision. The two researched divisions have distinct differences in product volume; one division produces volumes of ‘hundreds’, whereas the other division produces ‘millions’. Altogether the relevant engineering workforce for this study counts approximately one hundred.

AERO is a defence Aerospace Company based primarily in the UK which develops and produces engines for the aerospace industry. A typical annual volume is measured in ‘hundreds’. The customers are the defence departments of various countries. It is costly for AERO to make late-stage design changes, due to the need for re-certification of the engines. Failures in the market can obviously have severe consequences, but also simple failures are costly both to the customer and to AERO due to their service contract

Table 1. Graphical representation of the structure in the results and discussion sections.

TOPIC	MED	DEF	AERO	AUTO	Sub-section
Why (Q1)	What was the motivation for adopting RD?				4.1
How (Q2)	How was RD implemented? How is it applied today?				4.2
Challenges (Q3)	What were the challenges in the implementation?				4.3
Success factors (Q4)	What made the implementation successful?				4.4
Effects (Q5)	What have been the effects of adopting RD?				4.5
Similarities	5.1				
Differences	5.2 a	5.2 b	5.2 c	5.2 d	
Archetypes	5.3				

commitments. Mechanical product development is spread across several departments and sites, but 'several hundred' engineers have been involved in the RD programme.

AUTO is based in Sweden and develops and produces commercial trucks. The products have a long lifetime with a large variation in operating conditions, such as temperature spans, road conditions, use patterns, etc. Customers are highly dependent upon the 'up-time' of the truck and therefore any service on the product results in a relatively large 'cost of non-quality' for the customer. Therefore, the reliability of the truck is crucial for the brand value. The volume is typically measured in 'thousands', and the markets are spread around the globe. AUTO has several divisions with a total of 'thousands' of mechanical engineers.

In the following result section, interview findings are presented according to Table 1. Differences and similarities in the approaches are presented prior to a description and categorisation of four different strategies for RD implementation. A closing discussion of the applicability of the four different RD – archetypes in different Product Development – contexts is provided.

4. Results

The most central characteristics of how the four companies have implemented and applied RD are presented in summarised form in Table 2.

4.1. *Motivation for applying RD*

We looked at the companies' motivation to work with RD and noticed that all manufacture products where reliability is a key feature. Product failures lead to considerable losses for the users of the products, either directly in the form of a health hazard for the user (MED) or the operator (DEF) or indirectly in the form of 'down time' of the product, which means that the truck (AUTO) or airplane (AERO) is taken out of service and cannot create value during this period. Another observation is that the companies' production volumes range from 'hundreds' to 'hundred millions', indicating that RD can be relevant for both small- and large-scale production. This contradicts the perception that the authors meet in industry, where it is often stated that RD is only relevant for high-volume production. It can be argued that a common characteristic of the companies' products is that they have *high complexity* and/or *high performance requirements*, indicating that RD is especially relevant for this type of products, but it is beyond the scope of this paper to elaborate on this observation.

Table 2. Overview of the main findings from the interviews with the four case companies.

	MED	DEF	AERO	AUTO
Why	Delays in late design stages Shorter and more predictable lead-time	Internal cost of poor quality Resources tied up in control and inspection	*Cost of non-quality* Expensive 'in service' changes Cost of redesign due to validation procedures	*Cost of non-quality* Avoid failures in market Maintain brand reputation
How	Defined roles and responsibilities Robustness Cockpit with six KPIs and requirements	Gradual implementation of Six Sigma and DFSS-practices Defined System Engineer role	Training of engineers + chief design engineers Certification scheme with robustness	Toolbox of 15+ RD tools Training and coaching (after failed attempt using external trainers)
Challenges	Resistance to change RD seen as an add-on to existing development activities	Lacking adoption of RD-tools and methods Visualising the usefulness of DoE after to initial unsuccessful use	Different perception of the novelty in the initiative The initial process towards RD was over-formalised	Unsuccessful 'tool-pushing' by external consultants No acknowledgement of need for change
Success factor	Personal qualities and competencies of chief/lead engineers Coaching and support of lead engineers	Gradual implementation of Six Sigma practice Consistency in definitions of framework	Training and courses focus on chief design engineers Having tools that are used on daily basis	Engagement and training of middle management Transition from external 'tool-pushers' to internally driven processes
Effects	Guidance on how to develop good designs Increased transparency for management	Cross-functional collaboration Design reviews increased insight in design features	More insight into their own design & understanding of the product behaviour Saved time in product development process	Stronger focus on knowledge and facts Increased understanding of the root causes of failures

On the motivation for implementing RD, the companies gave two main answers: (1) Reduction of in-market failures and (2) Reduction of development lead-time and delays during ramp-up. AUTO stated that: '*You have some failures occurring hundreds or thousands of times. These are design failures. But other failures occurring only a few times are signs of lacking robustness*' (Figure 2). Over the years, AUTO has succeeded in removing the design failures through other initiatives such as design reviews, design optimisation, field analysis, customer feedback, warranty claims, and testing, but still experienced a 'tail' of failures that did not occur very often. RD was seen as the countermeasure to further reduce the 'tail' of the failure-curve. The motivation for MED was '*unexpected*

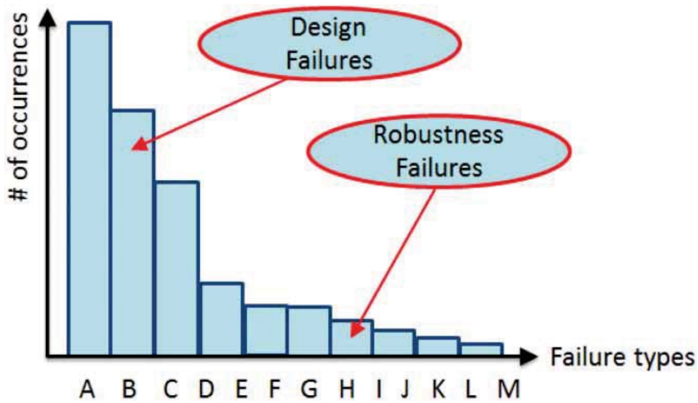

Figure 2. Graphical display of AUTO's distinction between design and sensitivity, based on the number of occurrences of the failure.

bumps on the road' in late development stages of projects. The lack of predictability in the project execution created challenges in project planning due to the many departments involved in the development projects. Furthermore, the market is very competitive, so delays in the launch of a product are damaging. AERO found their motivation in the avoidance of expensive 'in service' changes when design features had to be modified or replaced after customer deliveries. AERO was also motivated by the direct costs of non-quality, mainly via assessment and processing of concessions and quality plans. They wanted to reduce the extent of redesign, due to the costly 'recertification and airworthiness procedures'. DEF reported motivation to reduce the amount of resources spent on internal quality assurance, to lower the inspection demand and to secure a less marginal design even for products exposed to extreme environmental demands (temperature etc.).

Summing up, the motivation for applying RD was to reduce the cost of non-quality, but depending on the type of industry and product, the cost can take different forms (organisational turbulence, loss of brand value, cost of redesigning, cost of re-validation, etc.).

4.2. *How RD was implemented*

Implementing new methods in an organisation will typically involve changes in roles, processes, and methods, which again requires training and ongoing coaching. The four case companies have touched upon all of these aspects by offering training to their engineers and also to some extent, to managers. The extent of formal training was typically: MED 5–8 days, AERO approximately 5 days, AUTO several days, and at DEF, the extensive training on Six Sigma was expanded towards RD. For all companies, continuous informal training from internal consultants was also given. An interesting point here is the apparent need to include middle management and the technical project managers in this training. AUTO pointed out the difference between a manager being 'aware to and not opposing' a given method, and being 'an expert himself'. The point being that the 'pull' from management to use RD only comes when the manager is competent in the field. A similar experience was observed in AERO, where requests for internal RD coaching were limited, until the chief design engineers (who were the equivalent of a lead engineer in, e.g., MED) went through a training course, after which training requests saw a significant increase. It seems that – at least in the beginning – the application of RD methods did not come naturally, and if the immediate manager does not fully understand and know the methods, the engineers are not required to use them.

Another common trait has been the introduction of 'roles and responsibilities'. MED emphasises the appointment of a chief engineer with credibility in the organisation as one of the success factors and also mentions how they have worked to make the role of the lead engineers distinct and powerful, such that it is regarded with respect and honour. Besides this, there is still a central competence centre that can assist the projects with difficult analyses. AERO have installed an internal belting system, with green and black belts, thereby creating a clear hierarchy of facilitation experts. DEF has a less formal group of experts. However, AUTO has a dedicated group of project facilitators that help the project teams with making strategies for the reduction of performance variation.

There is a noticeable difference in how 'strict' the RD process is applied in the four companies. In DEF, RD is primarily based around structured design reviews, with a special focus on variation and tolerances, combined with a more cross-functional approach, where several departments are involved. AUTO and AERO provide a RD-toolbox from which the engineers can choose from a range of tools and methods. At the gate-review, the engineers will be asked which RD aspects they have considered and which strategy or method they have applied to ensure robustness, but are not as such required to use specific methods. MED has a stricter format, where the gate-review involves the presentation of a Robustness Cockpit, with current values of six KPIs, indicating the robustness of the product. The KPI-values are evaluated against specific target values in order to decide whether the product should pass the gate and move on to the next design stage.

Summing up, there is a common core in all four companies involving formal and informal training combined with specific roles and responsibilities, but the actual application of RD is quite different.

4.3. *Barriers against RD implementation*

The companies are reported to have experienced anything from large to very minor *barriers* on the implementation of RD. Within MED, some resistance could be traced back to a general resistance against change and a perception among the engineers that RD was an additional activity within product development, rather than an integrated way of working. A similar perception was identified within AERO, although this ranged from RD being perceived as a 'science project' to 'just good practice'. Also, some tools were applied wrongly in the beginning, because there was a perception that the full suite of tools should be used, rather than just the relevant ones. AERO experienced as stated by the RD Manager '*people coming out of a full-day QFD-session having created a 30 × 30 matrix and not wanting to ever apply RD again*'. Within AERO, there was also an awareness that '*over-formalisation of the RD Process*' should be avoided because such a process being governed and controlled by '*review panels and charters*' would have been a barrier for the application of RD. Within DEF, few direct barriers were experienced on the initiative as such; however, the company had experienced some barriers against applying powerful RD tools such as Design of Experiments (DoE). One of the barriers to applying DoE was seen in earlier unsuccessful attempts of application where no noticeable positive effect could be reported. AUTO had held a specific focus on RD for a decade and had adapted its approach for implementation on experiences from the early stages. An early attempt at implementing RD faced barriers as it was perceived among the engineers as 'tool pushing' by external consultants. At this stage they also found barriers in the low commitment to initiative among middle managers.

4.4. *Success factors for implementation of RD*

Any good initiative is useless unless it gets accepted and applied by the organisation. Therefore, we describe the companies' statements on success factors for implementing RD. Where the first attempt of tool-pushing in AUTO was evaluated as a failed attempt (Azadeh Fazl Mashhadi, Alänge, & Roos, 2012), they drew lessons from it and adapted the approach. The *success factor* in the 'second stage' of RD implementation was found in a much stronger engagement of the middle management level, the use of a learning alliances (Mashhadi et al., 2013), a broader training regime, and the explicit implementation into a unified global development process across several sites worldwide. AERO reported that their thorough training was one of their success factors. They had established a 'belt-system' similar to the known Six Sigma belt system (Aboelmaged, 2010) of acknowledging formal skills and training. They pointed out that even deeper training of chief design engineers had contributed to securing that the RD tools were used on daily basis. The design process at AERO encouraged the application of tools 'appropriately'. So, no demand on tool-applications was made but rather suggestions for use were made and a RD toolbox was provided. At DEF, one of the success factors was that the name of the product development framework was kept consistent. They had for more than a decade focused on Six Sigma and gradually reshaped the initiative to DFSS within manufacturing and development. Increased organisational awareness on variation and the active use of collaborative design reviews were reported. The reviews provided an arena to exchange critical objections on design issues related to lacking robustness and threatening sources of noise. The review was led by the systems engineer who was given a particular responsibility due to her outstanding technical and human skills, which made the review an arena to debate a certain design feature by chosen experts. MED pointed out the appointment of a chief engineer (overall technical responsible for all projects) with the right combination of technical and 'people' skills, combined with an internal credibility, as a cornerstone for the successful implementation of RD. Furthermore, MED have seen that, '*especially the lead engineers have undergone a fantastic development, driven by our internal Competence Centre and the external consultants, that has strengthened and changed the organisation*'.

Summing up, the success factors of the four companies comprise several elements of training and roles, including training of middle management to create pull, defining a RD process with a balanced use of tools and methods that fits the organisation and working culture, and careful selection of RD ambassadors in the role of lead/chief engineers.

4.5. *Effects on adapting RD*

All companies state that the aim of RD is to improve their products. Yet different arguments were used. Some used the perspective of customer satisfaction, some argued on spending less internal resources, some were strongly focused on robustness as an aid to reduce risk, and others argued that the focus on robustness gave better insight into the product behaviour based on an increased focus on fact-based decisions. In particular, MED pointed out the effect of improved guidance on how to develop good designs. This was achieved through the development and use of simple customised metrics providing engineers with an indication of the robustness of a given interface, at the point of design. The metrics are summed up in the so-called robustness cockpit, which according to the Senior Vice President '*provides increased transparency and* *collaboration for the project and management teams*'. The result has been that '*the large majority of projects in the portfolio are now executed at the right costs and with the right feature set*'. These indicators on robustness have been so successfully implemented that the Senior VP said '*implementing Robust Design is the best decision I've ever made. It allows me to sleep well at night, knowing the status of all projects*'. AERO named overall saved time in the Product Development process as one of the main effects in addition to a deeper and increased insight into their own design, giving a better understanding of the product behaviour when exposed for noise. AUTO on the other hand chose to point out the main effect to be a stronger focus on '*knowledge and facts as opposed to gut-feeling and tradition*'. One additional effect was the increased understanding of the root causes of failures, which had contributed to an additional reduction of undesired failures in the market. Effects observed at DEF included an improved cross-functional collaboration, practicing design reviews led by assigned systems engineers demanding clear statements on technological maturity throughout the development. None of the companies presented hard data documenting the effects of applying RD, but they generally had a 'feeling' that the resources spent on RD provided value.

5. Discussion

The interview findings and subsequent data analysis revealed similarities and differences related to the RD implementation. All four companies had a similar 'core' of activities related to training and roles and responsibilities, but used different approaches in other areas, here defined as four different archetypes of RD.

5.1. *Similarities in training, roles, and responsibilities*

Table 3 summarises the 'core' of RD – training, roles, and responsibilities.

Table 3. Similarities in training, roles and responsibilities.

RD approach	MED	DEF	AERO	AUTO
Training	Formalised training and substantial ongoing coaching from competence centre	Formalised training on handling variation through extended Six Sigma initiatives moved upstream towards RD	Formalised training + substantial ongoing coaching from competence centre	Formalised training + substantial ongoing coaching from competence centre
Roles and responsibilities	Lead engineer on each project plus an overall chief engineer with power to stop projects Competence centre with experts within each KPI. Allowance to pass gates	Project leader and strong experienced systems engineer promote sharing product/process insight at all organisational levels continuously	Chief design engineer on each project. Green and black belts as internal RD consultants	Many roles. Quality Manager, Knowledge Manager, Gate Auditor. Internal coaching, allowance to pass gates, etc.

Since all four companies have a very similar approach in terms of training and roles, it can be argued that this approach constitutes a best-practice for an RD implementation. Hence, organisations considering implementation of RD should include formal training for engineers and middle management (including lead and chief engineers), supplemented by informal and ongoing training. Furthermore, formalised and respected roles such as lead, chief and system engineers should be developed, along with well-defined responsibilities regarding project governance, proper use of methods, and execution of design reviews.

5.2. *Differences in process, gate-reviews, and tools*

Table 4 summarises the differences between the companies.

(a) At MED, RD was implemented in a formalised manner in the 'Development Manual' which also described the formal RD gate requirements. The established 'Robustness Cockpit' with six KPIs and target requirements directly linked to RD-activities secured continuous management attention and the ability for managers to judge the robustness maturity on ongoing projects. Altogether the successful implementation at MED is partly due to massive top-management pull and the ongoing coaching from their Competence Centre as well as an organisational culture based on compliance with company procedures. The reason for

Table 4. Differences in process, gate-reviews, and tools.

RD approach	MED	DEF	AERO	AUTO
Process	Development manual Robustness challenge prior to every milestone, where cockpit with metrics is presented	Design for Six Sigma reviews with a particular emphasis on the selection of robust design/process solutions	Loose process and intentional lack of KPIs. Instead a large tool suite offered along with guidance. Formalised training, but informal application	Global development process demanding that strategies are defined for dealing with variations
Gate-reviews	Clear targets for gate for every KPI	Defined reviews (Systems/ Preliminary/ Critical/Final Design) with attention to robustness	Projects given pass/ fail question: How do you plan to use RD tools in the project?	Projects asked about strategy for dealing with variation
Tools	Six custom KPIs. Very limited use of traditional RD toolbox	Wide use of SPC within manufacturing, designers are encouraged to use SPC-viewers and to design for robustness	Extensive use of traditional RD toolbox	Use of traditional RD toolbox alongside customised methods and tools

Note: SPC, Statistical Process Control.

applying this approach was the need for a common and objective way to give a leading indication of the robustness of the product, as early as possible.

(b) At DEF, we noticed a less tool-based approach on RD where the particular strengths were seen in creating a common design understanding in DFSS reviews. This company also showed barriers on implementing tools and methods such as DoE within the company. Reasons why this company adapted this approach are seen in its medium company size, its co-located premises with development and manufacturing, the strong local connection with a very stable workforce and the extreme demands on the products' performance which can result in a risk of products lacking robustness. In order to prevent this, sharing of design understanding similar to Poggenpohl (2004) gained importance and attention.

(c) Within AERO, we noticed that the use of a well-defined toolbox of more than 40 RD-tools was formalised and requested by management in a stage-gate process, similar to Cooper and Kleinschmidt (2007) where management explicitly questioned the use of RD-tools, and so this was a formal requirement to pass the gates. They further saw their success in extensive training, courses, and tools that were used on a daily basis. The toolbox was designed so that it not only described the theoretical side of the tool, but provided the user with suggestions on how this tool could be applied from a design context known by the employee, as also shown by Costa et al. (2006). This company reported that the positive effects of RD were a stronger and deeper insight into its own design and understanding of product behaviour which overall saved time in the Product Development-project. Altogether it appears that company AERO was not fully successful on implementing RD until their project chief design engineers went for training. This training created a 'pull' within the organisation that served as leverage for further organisational development on RD-practice.

(d) At company AUTO earlier attempts had shown negative effects of 'tool-pushing' by consultants with an exaggerated focus on the statistical side of RD, the archetype now based further application of RD as an integrated part of a Lean initiative, just as Matthias Kreimeyer and Lindemann (2011) promotes an integrated perspective. This archetype sees the commitment and training of middle management in addition to employee training and top-management support as crucial for making the workmode truly integrated. It eliminated the undesired perception of a 'RD-campaign', by adding 'softer' values related to collaboration and visualisation on top of the already known technical aspects of the company. To summarise, company AUTO had carried out several 'roll-outs' of RD initiatives with different approaches. They later underlined the need for middle management to gain deep knowledge on RD with the motto: 'They must *know* it to *require* it'.

5.3. *Four RD archetypes*

Based on the results, we suggest and label four different approaches applied in the companies – called Robust Design Archetypes: The (1) Metrics based, (2) Collaborative approach, (3) Formalised training scheme, and (4) Integrated approach. The metrics based approach was seen in company MED. The collaborative archetype on RD is observed in the company DEF. The formalised archetype on RD was seen in company AERO. The integrated approach on RD was shaped in AUTO over years of adapted training approaches (Table 5).

Table 5. Four identified archetypes of RD practice.

Company	MED	DEF	AERO	AUTO
RD Archetype	Metrics based	Collaborative	Formalised	Integrated

This research has yielded empirical insight into industrial practice on how RD is implemented and 'lived' within industry. It is important to notice the fact that product development is a clearly context-dependent activity and that 'the universal best practice' for applying a given initiative probably cannot be prescribed. As researchers, we also see the risk that these categories represent a potential (over-) simplification that does not cover all aspects of the initiatives. Whether adding additional companies to the case would have added further archetypes is a legitimate question that cannot be answered with an absolute statement prior to researching it. We are, however, confident that there is an upper limit on how 'fine-meshed' categories still make sense. The proposed archetypes should, therefore, be seen as a guide and a potential first step towards an improved mapping-tool for industrial RD-practice. These archetypes are therefore not to be understood to mutually exclude each other.

It is seen that the approaches are quite similar in terms of training and roles and responsibilities, whereas they differ substantially in terms of process, gate-reviews, and tools. It is also worth noticing that especially MED and AUTO have extended the existing RD toolbox even further and have developed new methods and KPIs which are not described in literature, whereas the two others to a larger degree have taken the existing RD toolbox containing, for example, DoE and transfer functions and made it part of their development process. As a final point, it is interesting that none of the companies could make a clear statement on the costs and effects of implementing RD. While there is no good reason for not making an estimate on the cost of implementing RD, the benefits are more complicated to estimate. One reason is that it is difficult to quantify the cost of non-quality in terms of, for example, loss of brand value. Furthermore, it is extremely challenging to document the effect of error prevention – how does one know which of the many design improvements due to RD activities would have otherwise become a costly failure further down the line? This is most likely an inherent weakness in establishing a well-documented business case for the implementation of RD.

6. Conclusion

Robustly designed products are insensitive to variation and provide the desired functional performance in spite of variations in use, deterioration, etc. Implementing and using RD principles are reported to be challenging in the industrial product development context in spite of its rich theoretical body of literature. In this empirical paper based on a series of interviews among 'best practice' companies on RD, we identify that the cost of non-quality is a common motivation for implementing it. We further identify industrial differences on RD and suggest four possible archetypes for implementing and applying it – consisting of a common core of training and formalised roles and responsibilities, supplemented by a (1) Metrics based, (2) Collaborative, (3) Formalised, or (4) Integrated approach. We have outlined the experienced challenges, barriers, and success factors of each approach, which paves the way for a potential assessment tool to determine which strategy will work best for a given company. This is valuable to organisations considering implementing RD, because they can gather inspiration from the description of four successful approaches and decide which best suits their needs, based on their own motivation, organisational style, available resources, and wanted effects.

Further work

As to the outlook, we see a potential for further research in consolidating the different RD approaches presented in this paper into a generic RD process with a set of relevant tools and methods for each design stage. Furthermore, there is a potential for developing a 'Robust Design Maturity Model' to measure the maturity of an organisation in terms of RD. Finally, there is a potential for looking into how to link the generic process with the maturity model, so that it is possible to configure an optimal RD approach for any given company, depending on the context of their organisation, market, product, etc.

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Appendix. A comprehensive listing of the main findings summed up in Table 2

Table A1. Overview of the main findings from the interviews with the four case companies.

	Device	Defense	Aerospace	Automotive
Why	Delays in late design stages Shorter and more predictable lead-time	Internal cost of poor quality (resources tied up in control and inspection)	*Cost of non-quality* Expensive 'in service' changes Cost of redesign due to rigorous approval and validation procedures	*Cost of non-quality* Avoid failures in market, to maintain brand reputation
How	Pilot projects Defined roles and responsibilities Robustness Cockpit with 6 KPIs and target requirements Training and coaching of engineers and lead engineers Updated development manual with formal RD gate requirements	Gradual implementation of Six Sigma and DFSS-practices Defined System Engineer role Training of design and manufacturing engineers Review procedure	Training of engineers + chief design engineers Certification scheme with robustness belts (green + black) Toolbox of 40+ RD tools Stage-gate process that explicitly questions the usage of RD principles	Pilot projects Toolbox of 15+ RD tools Training and coaching (after failing attempt on using external trainers) Updated global development process with formalised RD gate requirements (without metric targets)
Barriers	Resistance to change RD seen as an add-on to existing development activities	Lacking adoption of trained RD-tools and methods (e.g. DoE) after training Visualising the usefulness of DoE posterior to initial unsuccessful attempts of use	Perceived by some as a science project By others regarded as 'just good practice' (two extremes see above) The initial process towards RD was over-formalised	Unsuccessful 'toolpushing' No acknowledgement of need for change Poor integration into daily activities Lack of statistical knowledge

(*Continued*)

Table A1. Continued.

	Device	Defense	Aerospace	Automotive
Success factors	Personal qualities and competencies of chief/lead engineers Emphasising the importance of Chief/lead engineer roles on decision making Coaching and support of lead engineers	Gradual implementation of Six Sigma practice over time Consistency in definitions of framework (Six Sigma) despite of development in its content (added content)	Training and courses Having tools that are used on daily basis Training of chief design engineers Encouragement to apply tools 'appropriately', no demand but suggestions of use/provided toolbox	Engagement and training of middle management Transition from using external tool-pushers to internally driven learning processes Improved ability to communicate the importance of RD internally
Effects	Guidance on how to develop good designs Increased transparency for management Large majority of projects in portfolio are executed at right costs + right feature set	Cross-functional collaboration Design reviews led by assigned systems engineer demanding clear statements on technological maturity Increased insight in parameter influence on overall performance supports targeted definition of safety factors	More insight into their own design (understanding of the product behaviour as such) Saved time (overall in the PD-process)	Stronger focus on knowledge and facts (opposed to gut-feeling and tradition) Increased understanding of the root causes of failures Reduction of undesired failures in the market
Improvements	Earlier update of the product development manual Harder push to also apply RD in the early phase of product development	Daring to apply principles earlier/in more projects at the same time (faster roll-out) Utilise knowledge potential in gathered data from other projects/manufacturing	Having leading KPIs A better systems view and a more top-down approach	Further improve communication to/among engineers Continue existing knowledge sharing activities (homepage, posters, workshops, conferences, etc.)

Note: PD, product development.

9.5 Paper E

"A Robust Design Applicability Model"
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A ROBUST DESIGN APPLICABILITY MODEL

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Abstract

This paper introduces a model for assessing the applicability of Robust Design (RD) in a project or organisation. The intention of the Robust Design Applicability Model (RDAM) is to provide support for decisions by engineering management considering the relevant level of RD activities. The applicability assessment is based on two considerations: 1) Whether there is a correlation between the factors that are important to the project or organisation and the factors that impact from the use of RD and 2) What is the occurrence level of the given factor in the organisation. The RDAM defines RD to be applicable in organisations assigning a high importance to one or more factors that are known to be impacted by RD, while also experiencing a high level of occurrence of this factor. The RDAM supplements existing maturity models and metrics to provide a comprehensive set of data to support management decisions. The factors in the RDAM were derived by analysing a combination of RD literature and industrial cases involving RD. The RDAM is used on a case company to illustrate its use.

Keywords: Robust design, Design management, Organisation of product development, Design for X, (DfX)

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1 INTRODUCTION

The purpose of this paper is to present a Robust Design Applicability Model (RDAM) for measuring the applicability of Robust Design (RD) as a means of improving the intended performance criteria of a project and/or an organisation.

In order to achieve and maintain profitability and competitiveness, production companies are constantly striving to improve their processes. Within the field of product development and production, a wide array of frameworks and methods such as LEAN, Design for Six Sigma, Design for Manufacture, Reliability Engineering, Robust Design Methods etc. are available for supporting process improvements and for optimising performance parameters such as scrap rates, lead time, functional variation etc. Although all of the available frameworks and methods potentially create value for the organisation, there are significant costs of implementation and use. Limitations on resources and considerations as to how many changes the organisation is capable of handling simultaneously constitute a practical limit on the number of methods an organisation can implement at one time, as well as the level of depth each method is taken to. Hence, the management is faced with the decision on which frameworks and methods are most relevant in terms of improving the overall performance of the organisation and to which level they should be taken.

This paper seeks to identify and define ways of supporting this decision and is therefore targeted at managers and practitioners within engineering design and quality engineering, working with design processes and methods.

It is not the aim of the paper to make a comparison of various frameworks, but rather to present a model for assessing the specific framework of Robust Design, as experience and surveys have shown that the industrial uptake of RD is limited. This is done by answering the research question:

How can an organisation identify the applicability of Robust Design?

The paper opens with a Theoretical Background providing an overview of the existing state-of-the-art, followed by a Methodology-section, describing how the RDAM was developed. Then, the resulting RDAM is described along with an example of how it has been applied on a case organisation. Finally, the implications and further research potential of the RDAM are discussed and the conclusion sums up the main findings.

2 THEORETICAL BACKGROUND

The process of developing a new product comprises a number of phases, each containing certain activities (Pahl & Beitz 1984, Ulrich & Eppinger 2011). Depending on the size and type of the organisation, the process and activities can be more or less formally defined in a process model, e.g. a stage-gate model. The organisation then has an interest in optimising the types, levels and competencies of these activities. RD is an example of a set of tools and methods that aim to improve the reliability of a product's performance by reducing the sensitivity of the product's functions to variations in its design parameters. Robustness is seen as a subset of reliability: A reliable product is defined as a product with the ability to "perform its intended function during a specified period of time under stated conditions" (Elsayed 2012) and for a given variation of a product's design parameters, a robust product will perform more consistently and will therefore also be more reliable. The RD framework contains a wide array of practices (Hasenkamp 2009) and tools (Eifler et al 2013) and can potentially be applied at various levels in terms of which practices and tools are used as well as the resources allocated to apply them.

For organisations of a certain size there will be several activities running in parallel and resources are allocated to each activity based on the expected benefit to the organisation. As a part of defining the optimal level of activities within a given field, maturity measurements can be used. Measurement of project or organisational maturity on the topics of reliability and robustness are of interest both to improve business performance and to develop the products' robustness characteristics. The term "mature" is defined by Andersen et al (2003) to be "in perfect condition to achieve its objectives" which represents an unrealisable target for many organisations. When measuring maturity the question is therefore not "whether or not" the organisation's practices are mature, but rather "what is the level of maturity". Several guidelines for developing maturity models are provided and recommendations are summarised in Pfleger (1995), Maier et al (2012), Mettler (2011), and Tiku (2007). Maturity models should typically (i) Be tied to the needs of the organisation, (ii) Start small and grow according to needs and resources, and (iii) Support visualizing aspects of interest (of the process). On a general level this mapping and corresponding measurements are necessary parts of process improvements. Various maturity models are already available for measuring and benchmarking the organisation's maturity or capability within several fields; for example, Maier et al (2012) identifies 61 maturity models ranging from "R&D Effectiveness" to "Effective Teamwork". These maturity models are often based on an assessment of various entities on a predefined scale (Khoshgoftar et al 2009), with a clearly specified set of requirements necessary to reach the next maturity level. The nature of a maturity model can vary depending on the aim and scenario. They can be: 1) Descriptive, giving an 'as-is' picture of the current maturity level, 2) Prescriptive, defining the target levels of the organisation or 3) Comparative, comparing the maturity level with e.g. competitors, sites within the same organisation or an identified best-practice organisation. Assuming that advancing to a higher level requires organisational change, training and additional activities, advancing towards and maintaining a high maturity level requires resources. Therefore, reaching the highest possible level of maturity within all aspects may not be the optimal solution for the organisation. The management must consider the costs and benefits associated with each level of maturity and define the relevant target levels. Within the field of reliability and robustness, the Institute for Electrical and Electronics Engineers (IEEE) has developed a standard (IEEE1624 2008) that outlines eight different practices, including aspects such as planning, training, analysis and testing, supply chain management, failure analysis, verification and improvements. The maturity of each practice can be assessed on a defined Likert scale with five levels.

Information about the current maturity level could be supplemented by information about the relevance of the field in question, as shown in Figure 1. Performance metrics, such as production yield, customer complaint rates, process capabilities, launch date precision etc. give some indication on current performance. Perera (2006) gives an example of how reliability metrics can be used on product level and Ebro et al (2014) and Ebro et al (2012) list a series of relevant metrics for defining the robustness of a product. These metrics can be based on specific products or product lines, but can also comprise the entire product portfolio to show a more complete picture of the overall performance of the organisation. However, the metrics are descriptive - they do not contain inherent targets and do not provide information about their importance for the overall success of the organisation and in some cases, the relevant metrics may not be available or used at all. Finally, the metrics are not weighted or prioritised, i.e. they do not include information about the level of impact they have on the organisation, compared to other metrics. Essentially maturity models measure the level of activities and methods in an organisation, but do not provide information on the actual performance nor the relevance of carrying out the activities, meaning that there is a blind spot for the decision makers.

Figure 1. Maturity Models measure the activities, methods and skills of an organisation, but typically do not measure the aspect of applicability of the given field.

Ideally, decisions on whether to apply RD, and the level of resources to allocate to this set of activities, would be based on specific knowledge about both the maturity and the applicability of Robust Design. For example, it is not sufficient to know that the customer complaint rate is 0.6% and that the organisation is at 'level 3' in all aspects related to robustness - to complete the picture, it is relevant to also know how important in-use failures are to the organisation, as this can vary greatly depending on the product and market expectations. Because the aspect of Maturity is already covered by e.g. IEEE1624, the paper will focus mainly on the concept of Applicability.

3 RESEARCH METHODOLOGY

To identify how the use of RD impacts a company, a case analysis was applied, as this was considered to give a more authentic picture than theoretical descriptions of effects. Cases, which have had the direct involvement of one or more of the authors, either in the role as consultant, engineer or researcher were selected. The cases come from companies in four different European countries

(Norway, Sweden, Great Britain, and Denmark) and cover a wide range of businesses including defence, medical devices, aerospace and consumer electronics. The criteria for selecting the cases were the authors' involvement and knowledge of them. It should be noted that the identified set of impact factors therefore do not necessarily constitute a definitive, but rather a comprehensive set. The case descriptions are based on a combination of company statements, project reports, project descriptions, steering committee conclusions and ongoing discussions between the authors and the case companies.

The methodology builds on the assumption that if an organisation assign impact factors associated with RD high importance then RD is likely to be applicable in the organisation. The assessment of the applicability is further strengthened by also including an assessment of the occurrence-level of the given impact factor, as this indicates the current level of performance. As an example, if an organisation defines the factor *launch date precision* as highly important, and this factor is recognisedto be impacted by RD methods, and the percentage of launch date delays is high, then it is likely RD is applicable in that organisation.

The insights from the industrial companies are structured based on common characteristics of their initial undesired situations and the main impact factors they wanted to influence. An impact model is used to capture and visualise the case data, see Figure 2. In general terms an impact model describes the relationships between certain input factors and their corresponding outcomes. Impact models have different purposes and can be used to guide and support research or to establish a statistical relationship between variables and the corresponding validation of this relationship. Within research on engineering design, the impact model presented in Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) describes "the desired situation and shows the assumed impact of the support to be developed". Underlying the term "model" is an assumption that a "certain something" is likely to exist in reality. Models are simplified representations of reality, they are not theories, but they can be used to represent a theory. The DRM authors acknowledge that an impact model can be built up based on input from literature, but also various other sources such as "assumptions, experience, research goals, focus, questions and hypotheses" (p.20). This paper makes use of a combination of literature and experience from industrial cases to derive the presented Impact Model.

It is assumed that each of the factors in the Impact Model represent factors that are impacted by Robust Design and therefore an organisation that finds any of these factors to be important, could benefit from using RD. Therefore, each impact factor in the Impact Model is transferred to the RDAM, where they appear as assessment points that are rated by the organisation in terms of their importance. To illustrate the use of the RDAM, an assessment of a potential client for a RD consulting project was assessed to clarify whether the issues they faced (high impact + high occurrence) were likely to be impacted by using RD.

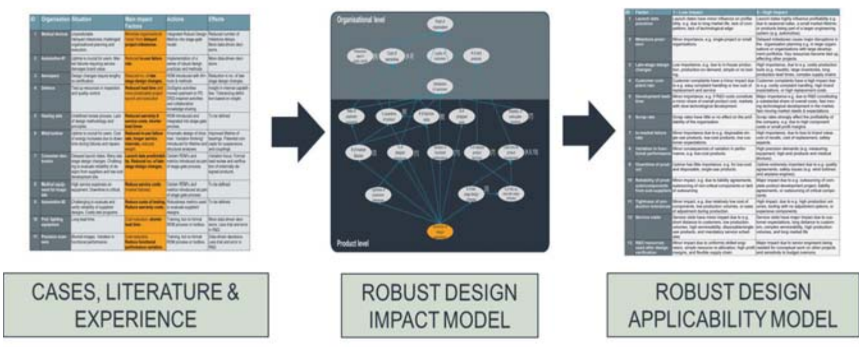

Figure 2. The Applicability Model is derived by analysing robust design-cases from industry and literature to identify the factors impacted by RD. These factors are visualised in an Impact Model and used as assessment points in the Applicability Model.

4 THE ROBUST DESIGN APPLICABILITY MODEL

This section describes the RDAM along with the intermediate results from the analysis of case studies and the Impact Model.

4.1 Impact Model

The Robust Design Impact Model is a generic model that ideally covers all factors related to the robustness of products. Although it is generic, individual organisations will assign different levels of importance to the different impact factors, and some factors may not be relevant at all to a given organisation. The impact model was developed using an analysis of industry cases known to the authors and combined with knowledge from literature on RD metrics and effects. The industrial cases were gathered from the authors' experience from different research projects and work as consultants in various European organisations. The criterion for the selection of cases was that the organisation has decided to work with RD and has initiated certain RD activities. The description of the cases can be seen in Table 1. Four of the cases are also described in more detail by Krogstie et al (2014). The cases represent various fields and come from four different European countries.

Table 1. Organisations that have worked with Robust Design. The table lists 1) their initial situation, 2) the main impact factors that they had identified as being important and that drove the Robust Design initiative, 3) the content of their Robust Design initiative and 4) the experienced effects. The highlighted impact factors were transferred to the Impact Model [1]

ID	Organisation	Situation	Main Impact Factors	Actions	Effects
1	Medical devices	Unpredictable /delayed milestones challenged organisational planning and execution.	Minimise organisational 'noise' from **delayed project milestones.**	Integrated Robust Design Metrics into stage-gate model.	Reduced number of milestone delays. More data-driven decisions.
2	Automotive #1	*Uptime* is crucial for users. Market failures requiring service damages brand value.	Reduced **in-use failure rate.**	Implementation of a series of robust design practices and methods.	More data-driven decisions.
3	Aerospace	Design changes require lengthy re-certification.	Reduced no. of **late stage design changes.**	RDM introduced with 40+ tools & methods.	Reduction in no. of late stage design changes.
4	Defence	Tied up resources in inspection and quality control.	**Reduced lead time** and more predictable project launch and execution	SixSigma activities moved upstream to PD. DfSS-inspired activities and collaborative knowledge sharing.	Insight in internal capabilities. Tolerancing definition based on insight.
5	Hearing aids	Undefined review process. Lack of design methodology and principles.	**Reduced warranty & service costs**, **shorter lead times**	RDM introduced and integrated into stage-gate process.	To be defined
6	Wind turbine	Uptime is crucial for users. Cost of energy increases due to downtime during failures and repairs.	**Reduced in-use failure rate, longer service intervals,** reduced weight.	Kinematic design of drive train. Variation thinking[1] introduced for lifetime and structural analyses.	Improved lifetime of bearings. Patented concepts for suspensions and couplings.
7	Consumer electronics	Delayed launch dates. Many late stage design changes. Challenging to evaluate reliability of designs from suppliers and low-cost development site.	**Launch date predictability. Reduced no. of late-stage design changes.**	Certain RDM's and metrics introduced as part of stage-gate process.	Variation focus. Formalised review and verification of externally designed products.
8	Medical equipment for hospitals	High service expenses on equipment. Downtime is critical.	**Reduce service costs** (market failures).	Certain RDM's and metrics introduced as part of stage-gate process.	To be defined.
9	Automotive #2	Challenging to evaluate and verify reliability of suppliers' designs. Costly test programs.	**Reduce costs of testing. Reduce warranty costs.**	Robustness metrics used to evaluate suppliers' designs.	To be defined.
10	Prof. lighting equipment	Long lead time.	Cost reduction, **shorter lead time.**	Training, but no formal RDM process or toolbox.	More data-driven decisions. Less trial and error in R&D.
11	Precision scanners	Blurred images. Variation in functional performance.	Cost reduction. **Reduce functional performance variation.**	Training, but no formal RDM process or toolbox.	Data-driven decisions. Less trial and error in R&D.

[1] Variation Thinking is a term used to describe that e.g. structural analyses, are not only based on nominal values, but also take into account the five different types of variation (Ebro et al 2012) that can change the geometry.

An impact model can contain multiple levels. As an example, the sensitivity of a design can impact the tightness of tolerances, which again can impact the ramp-up time and the scrap rate. The position of the factors in the Impact Model reflects the abstraction level of each factor. At the bottom of the model, the starting point is the "sensitivity of design parameters", which is essentially the main objective of RD. The sensitivity impacts on factors at a higher level, such as the number of market failures. This again impacts on factors at an even higher level, and ultimately, the profit of the organisation is impacted. Obviously, the profit of the organisation is a function of many other factors, but only the ones related to RD are shown in the figure. The identified impact factors from the cases were analysed and structured in a RD Impact Model as shown in Figure 3. Based on a combination of literature knowledge and experience, the impact model was extended with known impact factors not seen in the chosen cases. Furthermore, chains of impact factors were derived, i.e. each of the identified impact factors were analysed to identify the related impact factors in either direction.

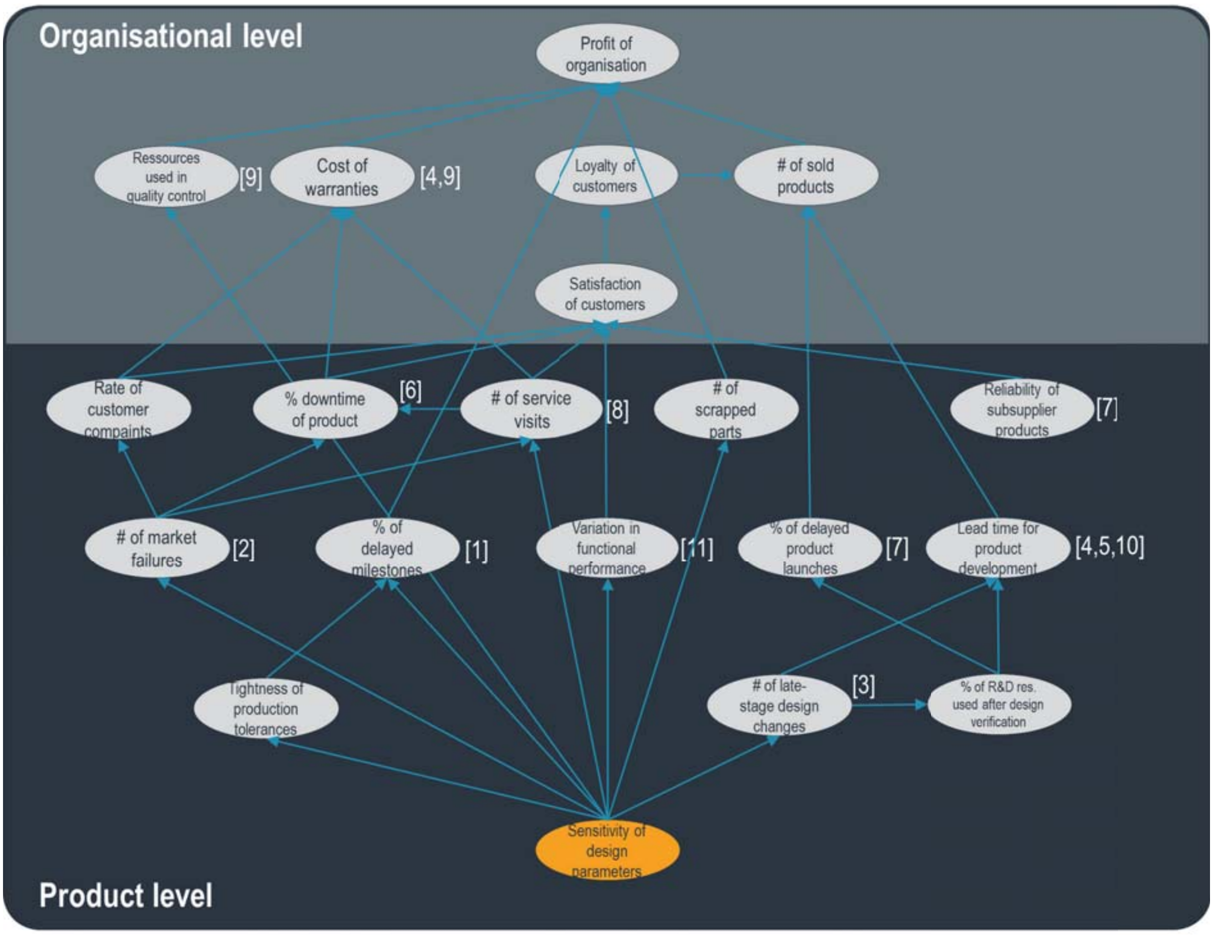

Figure 3. Robust Design Impact Model visualising the motivations and their associated impact factors identified in literature or in the case studies. Numbers in brackets [X] refer to the case numbers in Table 1.

The RD Impact Model in Figure 3 contains a structured overview of the factors related to RD, i.e. if RD was implemented, which factors in the organisation would potentially be impacted. An organisation wishing to improve factors that are included in the Robust Design Impact Model would thus benefit from implementing RD. Therefore, if an organisation assigns high importance to one or more of the impact factors then it is concluded, that RD is applicable in that organisation.

4.2 Applicability Model

The impact factors in the RD Impact Model have a certain level of impact on the overall success of any given product or organisation. For example, the predictability of the launch date of a new product in a consumer electronics company may have an extremely high impact, as 40% of the annual sales are placed up to Christmas, and therefore a delayed product launch in January is a significant loss compared to a planned launch in November. The impact factors in Figure 3 are used as assessment points or factors in the RD Applicability Model, which is presented in Table 2. The impact factors on the "organisational level" have not been included, because any company would claim that factors such as profit, number of products sold and customer satisfaction are important. In the RDAM, it is possible to rate each factor on a scale from 'low impact' to 'high impact' based on the degree of impact the factor has on the overall success of the project or organisation. The impact scale also includes a description and examples of why each of the given impact factors may or may not be important, which can support the organisation in defining the correct impact levels. The results of the assessment of the importance of the impact factors can stand alone, but if data is available, it can also be extended to include the occurrence of each of the factors. An example of this is shown in figure 4. It is the intention that this figure can be used for defining and scoping a subsequent Robust Design project, by suggesting relevant focus areas and performance metrics.

Table 2. Robust Design Applicability Model Factors from the Impact Model are applied as assessment points. Robust Design is applicable if any of the factors in the table have a high impact on the success of the product or organisation.

ID	Factor	1 - Low impact	5 - High impact
1	Launch date precision	Launch dates have minor influence on profitability, e.g. due to long market life, lack of competitors, lack of technological edge	Launch dates highly influence profitability e.g. due to seasonal sales, a small market lifetime, or products being part of a larger engineering system (e.g. automotive).
2	Milestone precision	Minor importance, e.g. single-project or small organisations.	Delayed milestones cause major disruptions in the organisation planning e.g. in large organisations or organisations with large development portfolios. Key resources become tied up, affecting other projects.
3	Late-stage design changes	Low importance, e.g. due to in-house production, production-on-demand, simple or no tooling.	High importance, due to e.g. costly production tools (e.g. moulds), large inventories, long production lead times, complex supply chains
4	Customer complaint rate	Customer complaints have a minor impact due to e.g. easy complaint handling or low cost of replacement and service	Customer complaints have a high impact due to e.g. costly complaint handling, high brand expectations, or high replacement costs.
5	Development lead-time	Minor importance, e.g. if R&D costs constitute a minor share of overall product cost, markets with slow technological development.	Major importance e.g. due to R&D constituting a substantial share of overall costs, fast moving technological development in the market, fast moving market needs & expectations
6	Scrap rate	Scrap rates have little or no effect on the profitability of the organisation.	Scrap rates strongly affect the profitability of the company, e.g. due to high component costs or small profit margins.
7	In-market failure rate	Minor importance due to e.g. disposable single-use products, low-cost products, low customer expectations.	High importance, due to loss to brand value, cost of recalls, cost of replacement, safety aspects.
8	Variation in functional performance	Minor consequences of variation in performance, e.g. low-cost products.	High precision demands (e.g. measuring equipment, high-end products and medical devices).
9	Downtime of product	Uptime has little importance, e.g. for low-cost and disposable, single-use products.	Uptime extremely important due to e.g. quality agreements, safety issues (e.g. wind turbines and airplane engines).
10	Reliability of products/components from sub-suppliers	Minor impact, e.g. due to liability agreements, outsourcing of non-critical components or lack of outsourcing	Major impact due to e.g. outsourcing of complete product development project, liability agreements, or outsourcing of critical components
11	Tightness of production tolerances	Minor impact, e.g. due relatively low cost of components, low production volumes, or ease of adjustment during production	High impact, due to e.g. high production volumes, tooling with no adjustment options, or expensive components.
12	Service visits	Service visits have minor impact due to e.g. short distance to customers, low production volumes, high serviceability, disposable/single-use products, and mandatory service schedules	Service visits have major impact due to customer expectations, long distance to customers, complex serviceability, high production volumes, and long market life
13	R&D resources used after design verification	Minor impact due to uniformly skilled engineers, simple resource re-allocation, high profit margins, and flexible supply chain.	Major impact due to senior engineers being needed for conceptual work on other projects and sensitivity to budget overruns.

4.3 Assessment

The assessment of the organisation can be done as either a self-assessment or an external assessment by e.g. a consultant. It is the intention of the model to allow for a fast and efficient assessment, taking no more than an hour. However, knowledge about the importance of the factors does require a relatively holistic view on the organisation's market situation, financial setup, service requirements etc. so the assessment is expected to be carried out at managerial level.

4.4 Scenario

The Robust Design Applicability Model (RDAM) can be used in various scenarios:

1. As an ongoing assessment of quality related initiatives in the organisation, in order to create a common picture of factors of importance for the organisation. Especially in organisations with large differences in the types of products in the portfolio, it may be beneficial to make an applicability assessment prior to each new project, to define the necessary level of RD related activities for the given project.
2. Prior to launching a quality improvement initiative, in order to become clearer on the main drivers for the project and to create a common understanding of the objectives. Specifically, the RDAM can clarify whether RD can be expected to create an impact on the key factors, i.e. the factors that are important to the organisation.

4.5 Interpretation of the results

The Applicability Model does not result in Metric(s) as such, but it can be visualised in different ways to show which factors are important to the organisation. Furthermore, the model can support the creation a common language and a frame of reference for discussing the importance of factors related to Robust Design within the organisation. It is also important to note that it is not the average score that is important to the applicability. What is more important is whether or not any specific factor has on the model has high impact on the project or organisation. If at least one factor has a high impact on the performance of the organisation, RD is applicable and should be taken into consideration as a means of improvement.

4.6 Case example

To enhance the understanding of the RDAM, an assessment of a case organisation is presented in Figure 4. The assessment is based on a real manufacturing company that develops and assembles high-end office furniture such as height-adjustable desks and chairs. Production volumes are small and the components are expensive and hence material costs constitute a significant part of the unit costs, which makes the frequent scrapped parts relatively costly. Most of the sales are concentrated around two annual furniture fairs and there is a history of delayed product launches, which have resulted in having to turn down potential customers that were interested in buying after having seen the products on the furniture fair. Although it is a small organisation, it is a high-end brand with clients spread all over Europe, and hence the service visits, which happen to approximately 5% of the products, are costly.

The assessment of the case company was carried out by the chief engineer in 20 minutes using knowledge readily available to him. Based on the results, it is seen that several of the RD-related impact factors are identified as having a high impact as well as a high occurrence level, making RD likely to be applicable in this company. Furthermore, the results indicates potential metrics to be used as drivers and effect measurements in asubsequent RD implementation in the company. In this case, scrap rate, number of service visits and launch date accuracy would be good metrics to use.

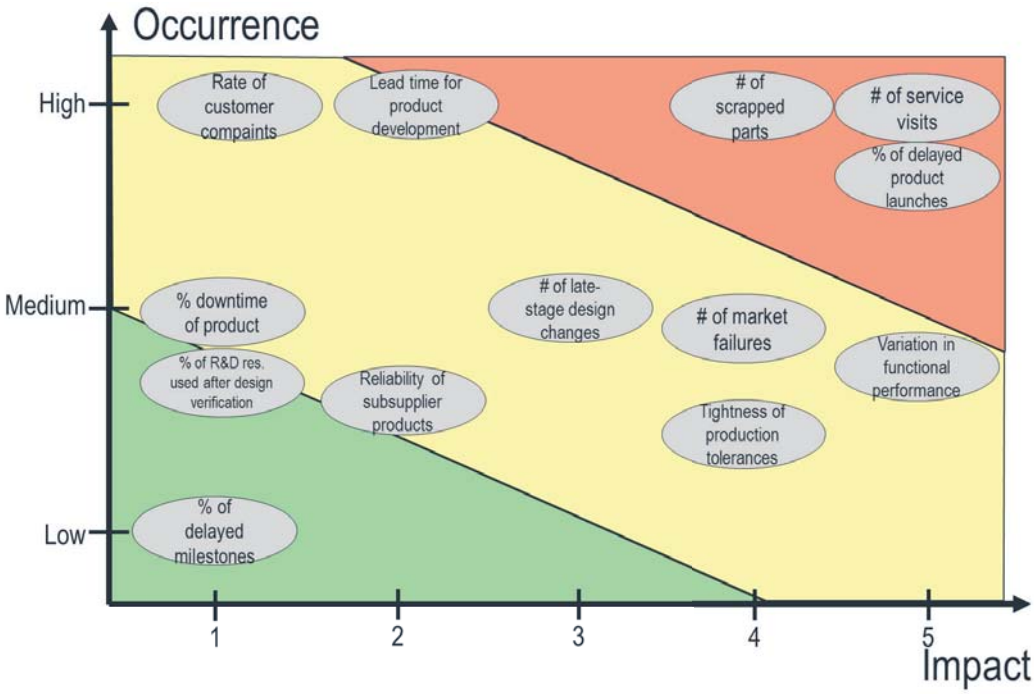

Figure 4. An example of the results of a RD Applicability Assessment in a small office furniture manufacturer. Several RD-related impact factors are identified as having a high impact and high occurrence rate, indicating that RD is applicable in the organisation

5 DISCUSSION

The **value** of the RDAM lies in its ability to identify whether or not RD is applicable for solving the issues of a given organisation. This increases the chance of using the right tool for the right problem, but the process of identifying the key factors also acts as a way of creating a common language and increases self-awareness in the organisation. Although the RD Impact Model is only used a stepping stone for deriving the RDAM, it is believed that the Impact Model itself also can contain valueable insights for an organisation, because it shows the path of impact factors all the way from the parameter sensitivity to the profit of the organisation. The link from parameters to profits can be used to create a shared understanding for the organisation. Furthermore, relevant metrics and targets can be set for each of the impact factors, such that the success of a RD initiative can be measured. Finally, the RDAM contributes by providing a simple overview of the potential benefits of RD - and by showing in the impact model how sensitive designs are linked to the profit and success of the company.

The RDAM has certain **limitations**. It is not necessarily exhaustive in the sense that it includes all relevant and potential impact factors of RD. Therefore it would be natural to extend and consolidate the model as more cases and literature become available. Furthermore, the current scale in the RDAM does not contain any metrics, which can make it challenging to define whether e.g. "launch date precision" has a medium or high impact. The scale could be extended by adding such metrics, which would allow for a more precise assessment. This t could also result in the assessment taking more time, because extra analysis work would be required to derive these metrics for the organisation and this would conflict with the original idea of creating a fast and efficient assessment tool. Finally, RD obviously has certain overlaps with other quality frameworks such as Lean Six Sigma and Design for Manufacture/Assembly etc. It should therefore be considered, whether other frameworks than RD are also applicable for addressing the important impact factors.

As to **further research** it is suggested to verify the model. Currently, the model indicates that if certain factors, e.g. launch date precision are important, then RD methods are applicable tools for impacting these factors. A follow up study could close the loop and verify that RD actually did affect the relevant key factors for each of the mentioned cases.

6 CONCLUSION

The purpose of this paper was to answer the question of how an organisation can identify whether RD is applicable. By analysing empirical data from various RD cases from multiple branches in the European industry, relevant impact factors of RD have been identified and applied as assessment points in an applicability model. The Robust Design Applicability Model (RDAM) fills a literature gap within engineering design theory on RD and it represents a simple and operative tool to identify the relevance of RD. Together with a reliability maturity assessment (e.g. IEEE1624) and relevant reliability performance metrics, the RDAM constitutes a comprehensive set of information that can support the decision as to the extent of robustness and reliability related activities to be required in a specific project or the overall organisation. The assessment can be performed internally or by a RD maturity mapping expert. In addition to identifying the applicability of RD, the model can create a common understanding in the organisation about the importance of specific impact factors and the connection between low-level factors (such as parameter sensitivity) and high-level factors such as warranty costs and profit.

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