Technical University of Denmark

Perceptual Robust Design

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Publication date:
2017

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

Citation (APA):
Pedersen, S. N., Howard, T. J., & Eifler, T. (2017). Perceptual Robust Design. Kgs. Lyngby: Technical University of Denmark (DTU). (DCAMM Special Report; No. S233).

Perceptual Robust Design

PhD Thesis

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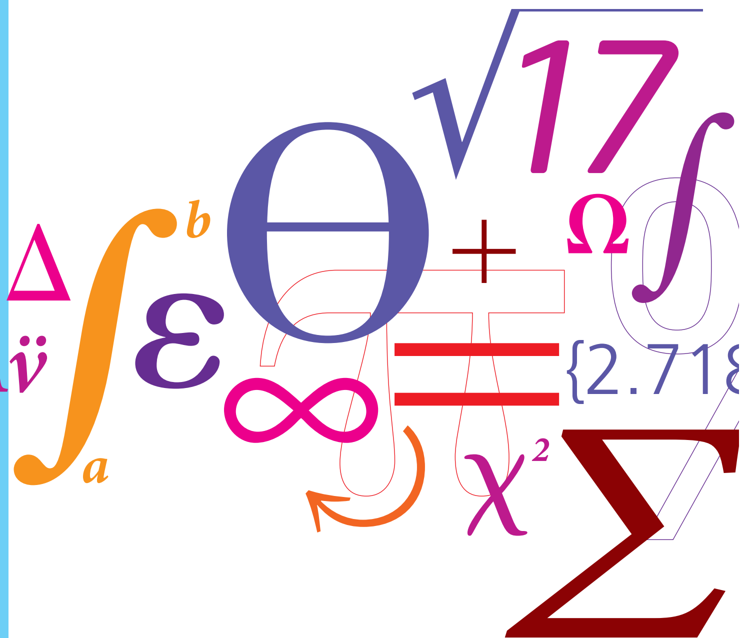

Søren Nygaard Pedersen

DCAMM Special Report No. S233
January 2017

DTU Mechanical Engineering
Department of Mechanical Engineering

Perceptual Robust Design

PhD Thesis
Søren Nygaard Pedersen
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ISBN: 978-87-7475-510-4

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Abstract

The research presented in this PhD thesis has focused on a perceptual approach to robust design. The results of the research and the original contribution to knowledge is a preliminary framework for understanding, positioning, and applying perceptual robust design.

Product quality is a topic that have received much attention from the literature, and for good reason. Defining quality as the ability to fulfil product requirements, the cost of non-quality does not only cause poor product performance, it also imposes huge direct costs for companies. Prevention, appraisal, and product failures are just a few examples of cost drivers. In general, the earlier quality issues are addressed the less costs they impose. Robust design methodology seeks to anticipate many of these quality issues by making product designs less sensitive to variation. The approach was first introduced by Genichi Taguchi in the 1980s and has since been expanded and refined. In more recent contributions, the notion of visual robustness has been introduced to the field of design research. However, contributions have only addressed the visual domain and no underlying theory on which to position or understand these studies have been presented. Therefore, this study set out to contribute to the understanding and application of perceptual robust design.

To achieve this, a state-of-the-art and current practice review was performed. From the review two main research problems were identified. Firstly, a lack of tools for effectively communicating robustness information as part of product requirements. And secondly, the need for a framework to understand, position, and apply perceptual robust design.

The first research problem was addressed with the introduction of the robust design requirements specification method. The method merges quality loss functions, a well-established robust design tool, with requirements development. For preliminary validation of the applicability and usefulness of the method three case study examples were presented revealing a promising potential. The second research problem was addressed with the introduction of the perceptual robust design framework that merged robust design methodology with Psychophysics theory. To evaluate the applicability and usefulness of the framework a case study was performed showing that product requirements could be loosened by up to 14.74%. However, the optimum for perceptual robustness was found to overlap with the optimum for functional robustness and at most approximately 2.2% out of the 14.74% could be ascribed solely to the perceptual robustness optimisation.

In conclusion, the thesis have offered a new perspective on robust design by merging robust design methodology with theory from relevant scientific fields. Furthermore, this new perspective has been operationalised through a preliminary framework for understanding, positioning, and applying perceptual robust design.

Resumé

Forskningen præsenteret I denne PhD afhandling har fokuseret på en perceptuel tilgang til robust design. Resultaterne af forskningen og bidraget til akademia er et *framework* til at forstå, positionere og anvende perceptuelt robust design.

Kvaliteten af produkter er et emne der ofte bliver adresseret i litteraturen, og med god grund. Defineres kvalitet som evnen til at imødekomme produktspecifikationer er omkostningerne ved manglende kvalitet ikke kun et spørgsmål om tab i omsætning forårsaget af dårlig funktionalitet, det er også et spørgsmål om stærkt øgede direkte omkostninger for virksomheden. Forebyggelse, kontrol og produktfejl er blot et nogle eksempler på kvalitetsrelaterede omkostningsfaktorer. En generel tendens er at jo tidligere i produktudviklingen at kvalitetsproblemer identificeres og adresseres jo mindre omkostningstunge er de. Robust Design Metodikken søger at forebygge mange af disse kvalitetsproblemer ved at gøre produktdesignet mindre sensitivt over for variation. Metodikken blev oprindeligt introduceret af Genichi Taguchi i 1980erne og er siden blevet udvidet og udviklet. I nylige publiceringer er ideen om visuel robusthed blevet introduceret. Disse bidrag har dog kun adresseret det visuelle domæne og der findes ingen grundlæggende teori der kan hjælpe med at forstå og positionere forskningen. Det har derfor været en målsætning for dette studie at bidrage til forståelsen og anvendelsen af perceptuelt robust design

Som led i processen blev et litteraturstudie foretaget for at kortlægge state-of-the-art og nuværende praksis for perceptuelt robust design. Litteraturstudiet afslørede to primære problemstillinger. For det første viste der sig en mangel på værktøjer til effektivt at formidle robusthedsinformation som del af produktkravene. For det andet viste studiet at der ikke fandtes nogen grundlæggende teori til at forstå, positionere og anvende perceptuelt robust design.

Den første problemstilling blev adresseret med introduktionen af *robust design requirements specification* metoden. Metoden forener *quality loss functions*, som er et centralt værktøj inden for robust design metodikken, med udviklingen af produktkrav. Som indledende validering af anvendeligheden og brugbarheden blev tre *case study* eksempler gennemgået, hvilket afslørede et lovende potentiale. Den anden problemstilling blev adresseret med introduktionen af en grundlæggende teori til at beskrive fænomenet perceptuelt robust design hvori robust design metodikken blev forenet med psykofysisk teori. Til at evaluere anvendeligheden og brugbarheden af fremgangsmåden blev et *case study* udført, som viste at produktkravsspecifikationerne kunne løsnes med op til 14.74%. Der var dog et overlap mellem optima for et perceptuelt robust design og et funktionelt robust design, hvilket betød at højst 2.2% ud af de 14.74% udelukkende kunne tilskrives den perceptuelle robusthedsoptimering.

I konklusion, er der i denne afhandling blevet fremlagt et nyt perspektiv på robust design ved at forene robust design metodikken med teori fra andre relevante felter. Derudover, er dette nye perspektiv blevet operationaliseret via en grundlæggende teori for forståelse, positionering og anvendelse af perceptuelt robust design.

List of core papers

As a paper-based thesis the core research and results have been presented in the three core papers listed below.

Paper A. Robust Design Requirements Specification: A Quantitative Method for Requirements Development Using Quality Loss Functions

Pedersen, S. N., Christensen, M. E., & Howard, T. J. (2016). *Journal of Engineering Design*

Paper B. Achieving a Robust Product Perception

Pedersen, S. N. & Howard, T. J. (2017). Manuscript submitted for publication

Paper C. Applying Perceptual Robust Design: A Case Study

Pedersen, S. N. & Howard, T. J. (2017). Manuscript submitted for publication

List of supplementary papers

In addition to the core papers of the thesis a number of supplementary papers has been published and submitted for publication. Paper S0, S1, and S2, are considered supportive papers as they are of relevance to the core research, but have not addressed any of the research questions posed as part of the research.

Paper S0. Variation Management Framework (VMF): A Unifying Graphical Representation of Robust Design

Howard T. J., Eifler T., Pedersen S. N., Göhler S. M., Boorla S. M. & Christensen M.E. (2017). *Quality Engineering* (In press)

Paper S1. Data Acquisition for Quality Loss Function Modelling

Pedersen, S. N. & Howard, T. J. (2016). C*onference proceedings for CIRP CAT 2016*

Paper S2. Robust Design of Sounds in Mechanical Mechanisms

Bøgedal, A., Munch, N., Howard, T. J. & Pedersen, S. N. (2015). C*onference proceedings for ASME IDETC/CIE 2015*

Paper S3 Product Promise Categorization

Pedersen, S. N., Thornton, Anna. & Howard, T. J. (2016). Manuscript submitted for publication

Paper S4 Exploring the Potential of Using Cognitive Modelling in Quantifying Usability of Physical Products: A Case Study Approach

Petersen, K. N. H., Pedersen, S. N. & Howard, T. J. (2017). Manuscript submitted for publication

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1 Introduction

Product design is important and it is important for more reasons than many realise. Many would point towards the appeal of the product appearance and the functionalities designed into the product as the most prominent goals of product design, which is probably true. However, if one isn't careful in defining a design that actually achieve these things, one might find that there is far between the vision for the product and the physical product being marketed. For instance, how often may a dishwasher fail before the appeal of the product is affected? Or, how much may the colour of a newly painted car fade before the appeal of the product is affected? These questions are important and is largely a matter of the variation introduced throughout the product lifetime, including production. The extent to which variation will affect a product is determined by the robustness of the product design. Therefore, lack of robustness can cause malfunctions and non-conformance, which historically have resulted in the recall of entire product lines, giving rise to massive costs for the companies. A fairly recent and particularly relevant case is the Toyota gas pedal incident from 2010, where approximately 2.3 million cars had to be recalled. The total cost was estimated to have reached 3.1 billion USD (Ramsey 2012)(Toyota 2010). In many ways the design was appealing, but due to unpredicted sources of variation and an insufficiently robust design an unacceptable number of failures occurred. Many more cases exist. Most are luckily solved before they reach the marked, but still late enough to impose massive costs to the company.

As a part of the Robust Design Program the present thesis is part of a larger research program. The overall objective of the program is to contribute to the field of robust design with new insight and understanding as well as new tools, methods, and applications. The Robust Design Program was kicked off in 2013 with support from Novo Nordisk A/S. Since, the team have grown to include seven research professionals and two student assistants, as per December 2016. The present thesis is the result of the work performed by one of these seven research professionals throughout his PhD studies. His background is in Biomedical Engineering and Management of Technology Development with a BSc from The Technical University of Denmark (DTU) and Copenhagen University and MSc from DTU. With a strong interest in product development and the technical aspects of business development, working with the challenges and opportunities of robust design research was a natural next step.

The scope of the Robust Design Program has been to investigate the entire spectrum of robustness increasing initiatives, through a framework called the variation management framework (VMF). In the VMF the spectrum of robustness increasing initiatives was divided into four domains (Howard et al. 2017) – customer attributes, functional performance, design parameters (DPs), and process variables. The present project has focused on the opportunities and challenges in the translation between customer attributes and functional performance. In other words, how product robustness can be increased in the link between the market and the product. More specifically this link is captured by the perception of the product. That is, how the objective appearance and performance of the product is perceived by users. To address this link from a robustness perspective the notion of perceptual robust design was introduced. A perceptual robust design being a design where the perceived variation is reduced to a minimum.

In Fig. 1, the VMF is illustrated, showing the four domains along each axis. Between each of the two adjacent domain axes a quadrant is formed. In each quadrant a function can be used to describe the link between the input and the output. The link between these functions and robustness are further elaborated on in Section 3.3.

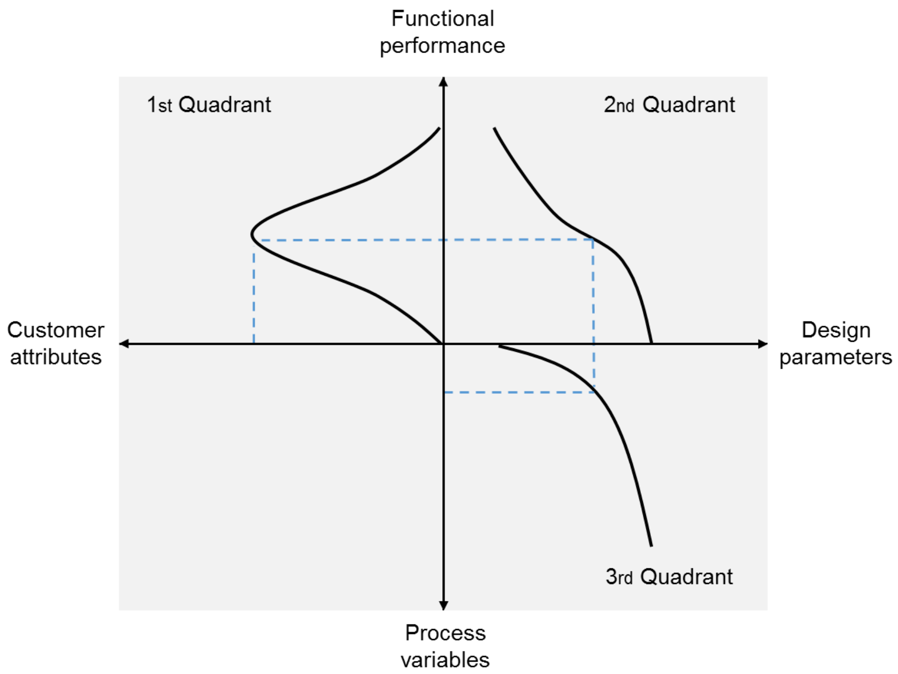

Figure 1. The VMF with four axes each representing a domain dividing robust design approaches into separate quadrants.

1.1 Background

Generally speaking robust design offers a potential solution to any risk problem related to output variation of a system. The design of said system would be the target of robust design and the result would be the change in output variation. The nature of the system can be mechanical, electric, social, etc. However, for this study only product systems have been considered.

Product variation is all around us. The lifetime of a pen, the force required to open a jar, or the protein content in the milk we drink. Even the deployment time of the airbags in our car or the lumen emitted from the bulbs in our house will have variation. Maybe we will not notice the variation because it is not deemed important by our cognitive system, maybe we simply cannot notice because our sensory system has its limitations. The variation, however, will always be present due to the chaotic nature of the world. Thus, variation is not only present in products it is also an inherent part of the environment in which the product will perform. Some users are stronger than others; some countries are warmer than others, etc. Due to these sources of variation products will often fail unless the relevant sources of variation have been considered in the design. In some cases companies fail to address this issue, because the company has not realized that variation will occur and operates from a nominal understanding of the world where complete accuracy is possible and achieved. In other cases, the company might have realized that variation will be present, but is unaware of the extent or the effects.

To avoid customers experiencing the negative impact of variation several strategies for avoiding and mitigating variation exist (Ebro & Howard 2016). One such strategy found with most companies is the use of quality control, where tolerance limits are used to specify an acceptable level of variation and everything outside the limits are scrapped, if detected. Another strategy is increasing the robustness of the design. Robustness is here defined as insensitivity to variation, usually meaning that the functionality of the product is insensitive to manufacturing variation etc. However, a product experience is not based on the objective performance of the product; it is based on the perception of the performance of the product, which is why the concept of perceptual robustness has been introduced.

A perceptually robust design is a design where the perception of the functionality or the appearance is insensitive to variations. Take for instance, the sound of a car door closing. Quantifying the sound in terms of frequency and intensity of the signal, an ordinary robustness optimisation would seek to maintain the nominal frequency and intensity. In perceptual robust design, however, it is the perception of the sound that is sought to be maintained. Here the frequency and intensity could be the input of the optimisation and the output would be the perceived pitch and loudness.

The difference between robust design and perceptual robust design originates with the fact that the human sensory- and perceptual system does not produce a 1:1 percept of the objective world. Human colour vision, for instance, is an interpretation of electromagnetic radiation in a limited frequency interval that has prevailed through an evolutionary process. Other animals have broader or narrower fields of colour vision driven by their individual evolutionary process. Furthermore, electromagnetic radiation corresponding to certain colours is not perceived equally. For instance, the ability to differentiate between some colour nuances is more important in an evolutionary context than others. The same applies to all sensory inputs. The resolution of sensory information and the processing of this information is formed by an evolutionary process which has been restricted by physical and chemical limitations. This skewed relationship between perception and reality is what can be utilised in perceptual robust design.

1.2 Problem

Many problems pertaining to perceptual robust design overlaps with those relevant to the more established robust design theory and practice. First and foremost the problem addressed by the method itself should be emphasised, which is to help avoid or mitigate output variation of a system by applying certain design strategies. The motivations for robust design are many. Besides catastrophic market failures there are many hidden costs to having sensitive designs (Christensen 2015), which will often first be revealed when scaling production. Fig. 2 illustrates how the product development resources are spent for four development projects in a consumer electronics company throughout the development lifecycle (Ebro et al. 2014). With a considerable amount of the resources spend after design verification and even after sales start, it is evident that late stage redesigns are a huge cost driver and problem to industry.

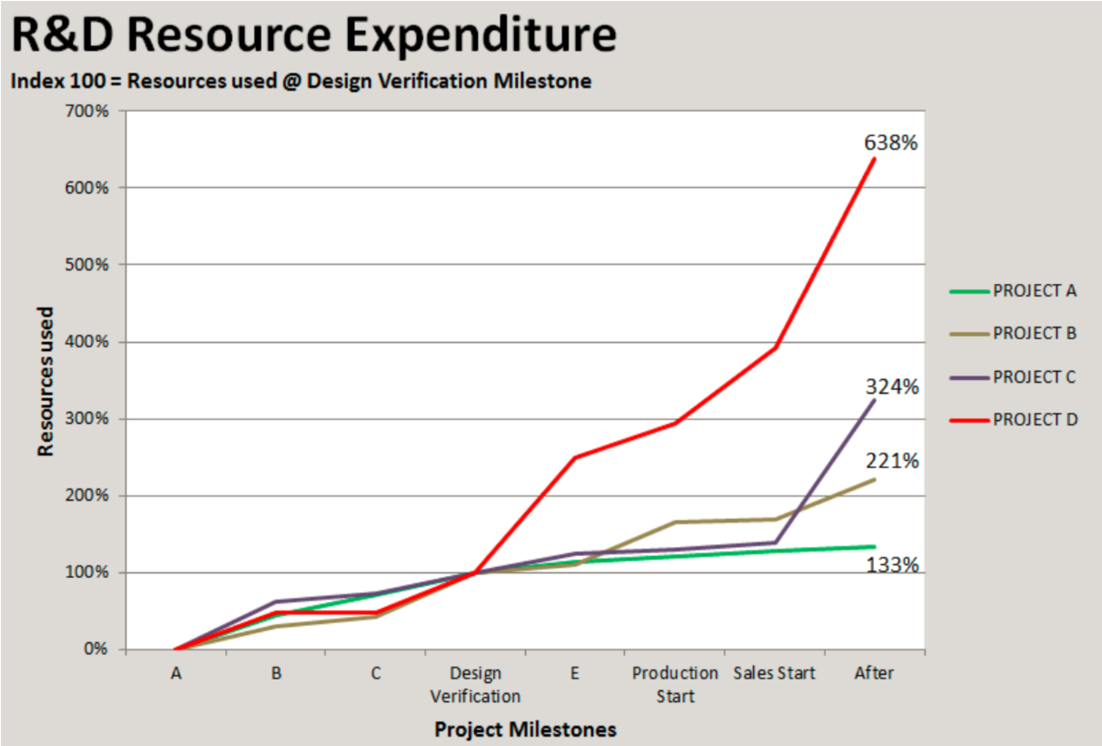

Figure 2. Product development resources spend for four development projects in a consumer electronics company. Percentages indicate the total amount of resources spend compared to the resources spend at design verification (Ebro et al. 2014)**.**

However, two additional overall problems related to the topic have also been identified. Firstly, the problem of when, to apply robust design. Both in terms of which design projects that holds a sufficient potential for improvement, but also in terms of timing and when in the design process to apply the method. Secondly, the problem of how to, apply robust design. Should the tools be used as stand-alone solutions or as part of a larger process? Should KPIs be put in place to monitor and benchmark? How can robustness be communicated between members of the design team and departments?

Some of these problems are primarily of concern and relevance to the industry whereas others pertain to academia. However, many of these problems overlap and must be addressed from both angles. As often seen in design research the fundamental motivation for robust design comes from the problems encountered in industry. Consequently, the best, and often only, way of properly validating tools and methods proposed by academia is by implementing them in their intended context in industry. In the following, some of the more specific problems encountered throughout the study are described.

1.2.1 Industry challenges

In industry, especially the practical problems and challenges of robust design come to show. Often the motivation for robust design comes from a desire to increase the predictability in production and in the market, leading to less scrap, fewer market failures, and overall reduced cost.
Starting at the motivation it can be hard for companies to assess the cost and benefits of robust design. Qualitatively, both cost and benefits can typically be described, but quantitative tools for making an actual cost-benefit analysis is lacking. This could potentially deter some companies from investing in robust design. Also, it makes it hard to determine the appropriate extent of an investment into robust design. Looking specifically at perceptual robust design both the theoretical basis and practical

guidelines for implementation are lacking. Consequently, information on the impact and suitability for specific products, companies, and markets are also lacking.

If a company decides to make an investment into robust design, new challenges arise. A number of approaches exist for implementing robust design, but it can be hard to determine which method(s) to use and how to apply them. Especially, the requirements and specifications domain present a challenge as established requirements and specification tools rarely presents an option to specify robustness requirements and communicate robustness related pitfalls. Not being able to communicate such information certainly presents a challenge to the use and dissemination of robust design. For many design engineers the statistical considerations required to explain and assess the benefits of robust design are unintuitive and therefore easy to forget or underestimate, why some quantified or potentially visual assistance could be beneficial. RD&T Technology offers a tool for simulating and visualising statistical variation (see Fig. 3), but despite its many applications other ways of supporting the process might offer new insights and value.

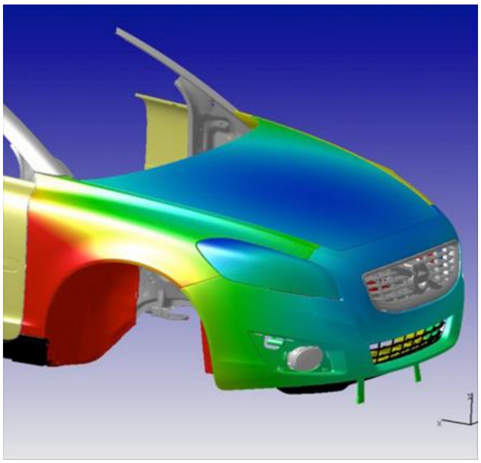

Figure 3. RD&T visualisation based on a stability analysis showing the geometrical sensitivity of a car design (RD&T n.d.)**.**

1.2.2 Academic challenges

The academic challenges in robust design are to a wide extent defined by the industry challenges. However, despite being primarily motivated by practical and current problems some challenges are of a more theoretical nature. Especially, the development of the underlying theory for new methods and approaches, which have not yet been implemented in industry, is where academia finds its relevance.

The development includes the forming of a theoretical basis, design of tools and methods, and some form of validation. In the development of new tools and methods, there has been little progress in the first quadrant. One of the main challenges here is the necessity of combining several fields of research to both describe the mechanical mechanisms found in products and the more biological and psychological mechanisms of human perception. Simply put, while there have been studies quantifying the “visual robustness” (a sub-set of perceptual robustness) of product concepts, these have been applied to a very limited number of products (mobile phones and cars) and to very specific features such as split lines. However, there is no underlying theory related to perceptual robustness on which to position or understand the contributions of these studies. A good underlying theory and framework related to perceptual robustness will help to identify the full range of potential application areas and relevant theory and methods that can be adopted from other research.

1.3 Aim and objectives

The overall aim of the project was to contribute to the understanding of product robustness by providing information or methods to improve product designs in terms of robustness. As part of a larger group this study has especially focused on perceptual robustness which particularly aims at improving product design in terms of loosening quality requirements and/or increasing customer satisfaction. Both outcomes can be translated into an increase in profits. The first option will mean less scrap for a given production system and throughput, which translates directly into lower material costs, and the latter option will produce more satisfied and loyal customers, which can lead to more sales or willingness to pay more per product. To achieve this aim the primary objectives have been to:

1. Clarify the challenges related to perceptual robustness.
2. Prioritise these challenges and form a strategy for addressing the most relevant ones
3. Conduct the required research and produce results that would contribute to the understanding and improvement of product robustness.

In Section 1.2 some of the main challenges in robust design research were listed. To ensure an efficient use of research resources these challenges have been divided and addressed by separate PhD projects in the Robust Design Group. For the present study, which is particularly close to the requirements specification process the problem of communicating robustness information was addressed as part of the overall project.

In the impact model shown in Fig. 4 the intended impact of the research is illustrated. The green boxes are the main impact areas and the blue boxes are the secondary impact areas. The boxes with red borders represent the focus areas of this study.

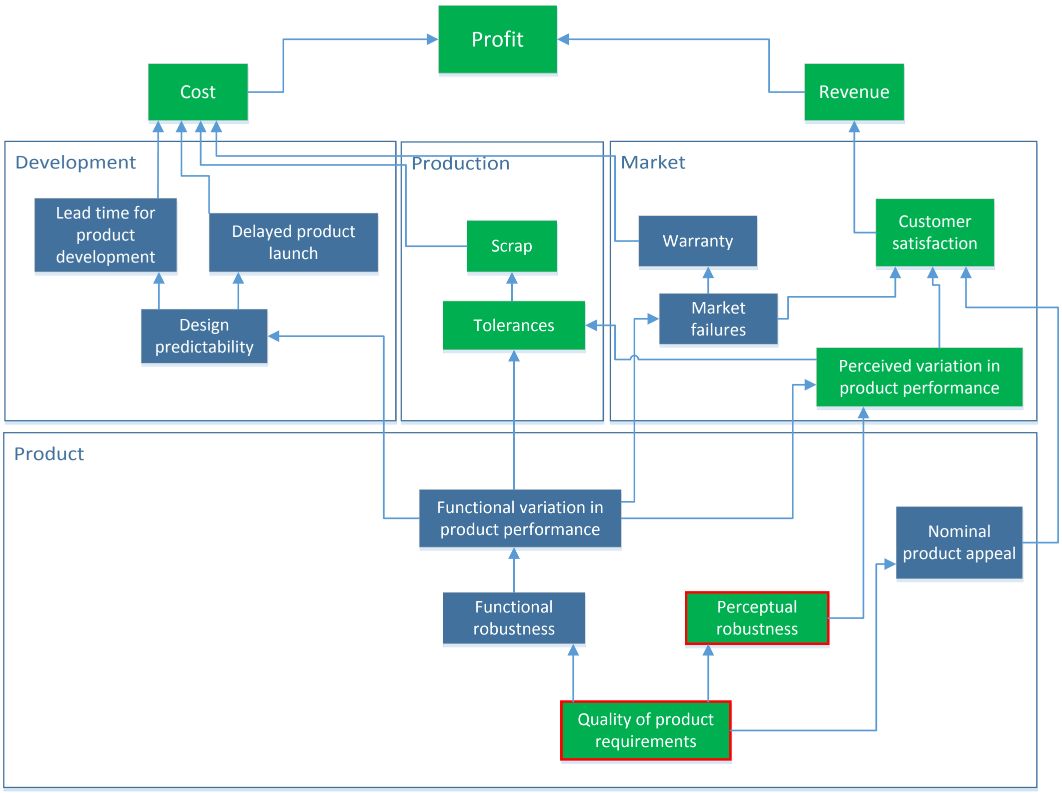

Figure 4. Impact model mapping relevant areas of product development. Green boxes indicate primary impact areas, blue boxes indicate secondary impact areas, and red border boxes indicate where the project has offered support.

The model is by no means exhaustive. Rather it shows the immediate impact areas and the areas which are typically used to explain and validate the impact of robust design. The causality of the model is given by the arrows. By improving the means for communicating quality loss- and robustness information, the quality of product requirements can be traced on to produce both a cost reduction and a revenue increase. These benefits can be achieved through a more effective design process and better design optimisations, each by multiple paths. One of these paths goes through the perceptual robustness of the product. As the primary focus of the study this is where the most research resources have been placed. Increasing the perceptual robustness will create more insensitive systems, which can be utilised by loosening tolerances or by reducing the perceived variation in product performance and thereby increase customer satisfaction.

1.4 Research questions

The process of capturing the aim and objectives in a number of research questions helped structure the project and concretise the research to be conducted. How open-ended the questions were formulated depended on the topic to investigate. The questions were meant to support the DRM strategy described in Section 2.2. Therefore, some of the research questions are of a descriptive nature where others are of a prescriptive nature.

Research question 0 (RQ0) was formulated to help scope the project and to shed light on any theoretical or practical challenges. Placing the research relative to the other quadrant of the VMF was important, both in order to properly divide the research efforts and to define interfaces. To capture the above, RQ0 was phrased as:

RQ0 – How does perceptual robust design fit with the remaining robust design theory?

Next, research question 1 (RQ1) addressed one of the general challenges found during the initial clarifying research, answering RQ0. The general challenge in question was how to accurately and efficiently communicate robustness information from market studies to the design engineers. This problem was considered a bottleneck and was therefore essential for a successful utilisation of robustness information. To capture the above, RQ1 was phrased as:

RQ1 – How can robustness information be better communicated between departments in the requirements specification phase?

Having addressed the challenge of communicating robustness information, the field of perceptual robust design was investigated. First step was to clarify existing related literature and how the issue was currently dealt with in academia and industry. To capture the above, research question 2 (RQ2) was phrased as:

RQ2 – What is state of the art and current practice for perceptual robustness?

Building on the results from answering RQ2, research question 3 (RQ3) went into more detail in identifying potential approaches for substantiating perceptual robust design, both in terms of existing approaches and new opportunities. To capture the above, RQ3 was phrased as:

RQ3 - What theories, metrics and data are available for designing perceptual robustness into products?

The last research question, research question 4 (RQ4), addressed how the implementation of perceptual robust design could be achieved in practice. When developing theoretical approaches to a practical problem it can be hard to foresee the obstacles and limitations that apply. The value of a tool is not only determined by its potential benefits, the applicability must also be considered. To capture the above, RQ4 was phrased as:

RQ4 - How can perceptual robustness theory be utilized in a product design?

These five research questions laid the foundation for the study. Each of them has been addressed by the studies conducted throughout the project. The extent to which the questions have been answered has varied and will be discussed for each question in Section 4.

2 Research approach

In this section the overall strategy for the PhD project is described. The purpose is to provide the reader with a better understanding of the structuring and rationale behind the approach and to describe the overall validation process of the findings and contributions of the research.

2.1 Research area

The research conducted as part of the PhD study has contributed to and drawn on existing research from several fields. How existing research has been used has varied depending on the context. Some fields have been a part of the foundation for the conducted research whereas others have solely provided inspiration or tools.

In Fig. 5 the hierarchy of research fields to which the present research has contributed is shown. Each field encompasses many frameworks, theories, methods, tools, approaches, etc. In Section 3 the theory relevant for the understanding of the present research is introduced.

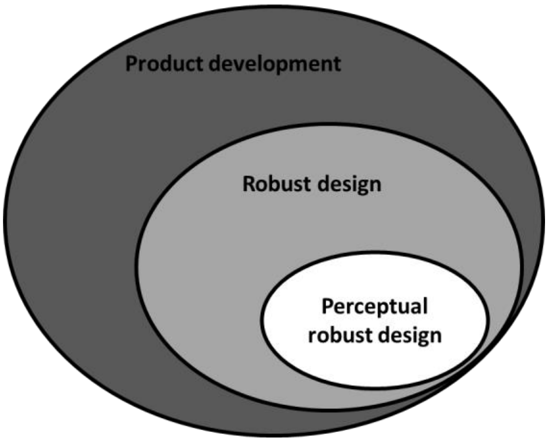

Figure 5. Research area model showing the hierarchy of relevant research areas.

The main focus of the thesis, perceptual robust design, is considered a part of the robust design theory, which again is part of the product development theory. Many other synonymous and overlapping fields exist. For instance, engineering design is closely related to the field of product development. However, as the engineering design process can be considered more of a general problem solving strategy, product development is here used to describe the underlying field of research as the focus was aimed at exactly, product development. Likewise, robust design is often considered part of quality engineering. However, as the field of quality engineering includes a wide range of research that has been deemed largely irrelevant to the present project, the focus has been solely on robust design.

2.2 Research methodology

As a point of departure the approach of the project has followed the design research methodology (DRM) (Blessing et al. 2009). The DRM approach offers a framework that helps guide the research towards a more rigorous and thorough output. Most journals and research institutions have a set of requirements or a definition of “good practice” when assessing a piece of research. The DRM successfully captures the common requirements for and definitions of good research by structuring the research in four research stages, shown in Fig. 6. In the figure the basic means and main outcomes for each stage is shown along with arrows indicating the order of actions and the iterative nature of research.

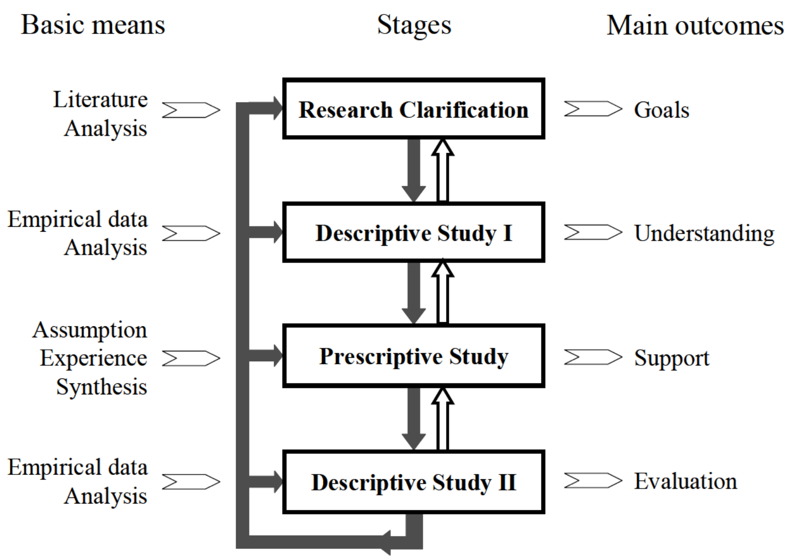

Figure 6. DRM framework (Blessing et al. 2009).

In the research clarification stage an understanding of the existing state is established and goals for the research are formulated. This is achieved with basis in literature studies, but could also include practical findings. One of the crucial steps in defining goals is to identify realistic measures for validating the findings. The descriptive study I stage aims at building a more focused and thorough understanding of the existing state scoped with basis in the defined goals. Correlations, or ideally causalities, are identified to provide the most effective and efficient support. Also, being able to quantitatively or qualitatively describe the existing state could provide a benchmark for later validation. Following, in the prescriptive study stage a solution, or support, is introduced to help achieve the defined goals and transition from the existing state to a desired state. Finally, in the descriptive study II stage the state achieved after providing the support is analysed and evaluated to assess to what extent the goals have been achieved.

The framework applies not only to PhD project research it also captures what is required for many types of journal publications. As a paper based thesis, the present project has aimed at producing papers for publication throughout the course of the project. Therefore, the DRM framework has also helped guide the individual research included in each paper.

2.3 Research design

The authors of DRM recognise that research is not always linear and that the scope and goals of an extended research project often will be subject to reiterations, modifications, and re-evaluations. The present project has been no exception. Modifications have been made along the way to adapt the research to the opportunities and obstacles that appeared. Based on the research from the research clarification stage, the project was early on divided into two, addressing two separate research problems. The first problem to be addressed was how to better communicate robustness information and the second problem was how to increase the perceptual robustness in products. Looking at the research questions, the robustness communication problem was captured by RQ1 and the perceptual robust design problem was captured by RQ2, RQ3, and RQ4. The DRM approach was applied to each of these problems, with the exception of the research clarification stage as it overlapped for both studies.

In Fig. 7 the relationship between research problems, research questions, DRM stages, and article contributions are illustrated. Articles related to the robustness communication problem are shown in blue nuances and articles related to the perceptual robust design problem are shown in grey nuances.

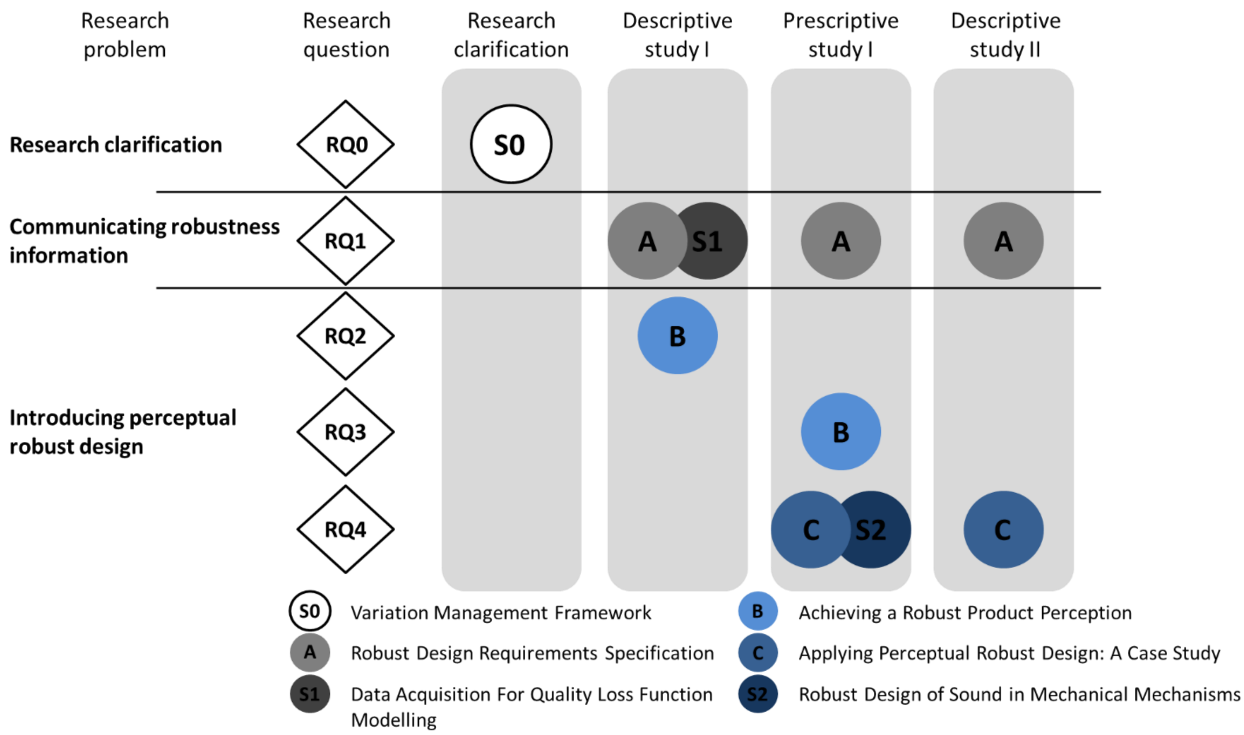

Figure 7. Research overview showing the relationship between research problems, research questions, DRM stages, and the contributions made.

Paper A, B, and C are the core papers for the thesis and represents the core research and contribution of the thesis. They are further described in Section 4 and can be found in full length in the appendix. Paper S0, S1 and S2 are supportive papers, meaning they are part of the supplementary papers, but with some relevance to the research included in the thesis. Paper S0 helped position the present research in relative to other robust design approaches and is briefly covered in section 3.1, paper S1 addressed an issue of definitions found in paper B, and paper S2 provided supportive data that was used in paper D.

2.4 Validation plan

The validation of the research has been carried out inspired by the validation strategy proposed by Blessing and Chakrabarti (Blessing et al. 2009) dividing the validation into two categories – applicability and usefulness. Furthermore, errors, procedures, and equipment have been evaluated for the appropriate experiments to ensure reproducibility. This is referred to as research verification.

As the perceptual robust design has been the intended mean to achieve the underlying goal the applicability of the proposed support has primarily taken basis in the work processes of design engineers. Ideally, case studies should have been conducted to test technical and use related aspects of the support. However, due to time constraints these case studies have been carried out combining technical empirical data, and theoretical analysis.

Validation of the usefulness heavily depends on the aim of the research. With the defined aim of contributing to robust design theory through the perceptual domain the underlying goal has been to improve the quality and profitability of products. An account for the link is shown by the impact model presented in Fig. 4. Case studies have been carried out in industry to validate the usefulness of the support. However, with a vast amount of influencing factors and a long way to market for the relevant case product, it has been unfeasible to attempt to measure the impact in terms of profit. Instead, factors with a strong causal link to profit, but closer to the point of impact, have been identified as more appropriate measures of usefulness. These measures of usefulness counted the tightness of quality control requirements and customer satisfaction rankings. Given the time constraints and with customer satisfaction rankings requiring user studies, the tightness of quality control requirements was identified as the most appropriate measure of success. Given the focus on perception, the measure of success was further narrowed in to requirement specifications under the assumption that product requirements are defined with basis in the perceived performance of the product.

2.5 External research activities

The field of design research is closely linked with the needs found in industry, both in the form of challenges and opportunities. Therefore, if support offered by academia in the form of methods, tools, or frameworks for some reason does not address a conscious or unconscious, present or future need in industry, it would be hard to argue its relevance. An understanding of said challenges and opportunities found in industry is therefore essential for conducting relevant design research.

In order to obtain an understanding of current practice in industry and the challenges and opportunities that exists a significant part of the research has been conducted at industry sights or in close collaboration with industry professionals. Likewise, on the academic side, the exposure to external research environments has been a high priority to further the scientific approach used to conduct the research and scope the focus of the project.

Throughout the PhD project three conferences have been attended. The Design 2014 conference in Dubrovnik, Croatia, the ASME IDETC/CIE 2015 conference in Boston, MA, USA, and the CIRP CAT 2016 conference in Gothenburg, Sweden. At the Design conference new research inputs were obtained as workshop co-facilitator. At the two latter conferences, research were presented and afterwards published as papers in the respective conference proceedings. In addition to the presentations the conferences also offered a rich exchange with other researchers in related fields.

In addition to conference attendance, several other external research environments have had an impact on the project. First and foremost a considerable part of the research has taken place at Novo Nordisk Device R&D in Hillerød, Denmark. Being a large company with more than 40,000 employees, this has offered valuable insights into the practical challenges large companies are facing in general and in relation to the use and implementation of robust design.

Furthermore, in the autumn 2014 a one day trip was made to Chalmers University in Gothenburg, Sweden. The trip included a tour and presentations from several staff members followed by networking and exchange of ideas and perspectives. With a considerable overlap in research focus between the DTU Robust Design Group and several of the research groups at Chalmers, the trip resulted in many inspiring talks and relevant references, which has been used in several of the publications presented as part of the present project.

In the summer and autumn of 2015 a four month stay as visiting researcher at MIT Sloan School of Management hosted by Professor Steven Eppinger was arranged. The stay included talks with several expert scientists where the present research was evaluated along with new angles and perspectives on the topic. In parallel, a 6 week internship with Dragon Innovation, a design for manufacturing consultancy, specialising in start-up companies, was arranged. The internship was hosted by variation risk management expert Anna Thornton. In comparison to the practical experiences from working with Novo Nordisk Device R&D the internship quickly showed how the practical challenges were very different for smaller companies and start-ups. To address some of the challenges found with start-ups the internship resulted in a journal article titled Product Promise Categorization. As part of the stay, a trip was also made to Cooper Perkins, a technology and innovation consultancy. During the visit, research from the present project was presented followed by a discussion about research methods, perspectives on product robustness, and the main challenges found in product development.
Lastly, to experience external research environments the IS3E Spring School was attended at the Technical University of Munich in Paderborn, Germany and an academic program on systems engineering were attended at MIT, Cambridge, MA, USA.

3 Theoretical basis

In this section the theoretical basis for the project is presented. It includes the scoping of the theoretical basis and a brief introduction to relevant theories followed by a description of their relevance to the project.

3.1 Scoping the theoretical basis

As described in section 2.1 the aim of the present research has been to contribute to the field of product development through advancement of the field of robust design. With the intention of the present research to contribute to the product development process it has been important to understand these processes. This understanding has been built from practical experiences and literature studies (see Section 2.5).

Restricting the contribution to the field of robust design implied a number of limitations. These limitations were captured quite well by the name of the approach. First, the meaning of robustness can be translated into insensitive to variation (Taguchi 1986). In other words, the approach is not trying to reduce or avoid the incoming variation, rather it focuses on the qualities of the system to which the variation is an input. Secondly, the approach addresses the design of systems as opposed to other quality engineering approaches, such as quality control, which focuses on the measurement and testing of designs. As such, quality control will often be closely related to robust design and also often provide the best means for validating the impact of robust design. However, supporting these processes is not considered a part of the aim of the present research.

Zooming further in on the field of robust design the present project has focused on the perceptual side of robust design. Scoping the research for this particular focus, was addressed by RQ0 – How does perceptual robust design fit with the remaining robust design theory? The results of the research carried out to address RQ0, which were presented in the supplementary paper S0, helped delimit the field of perceptual robust design and showed how the aim of the present research fits with the remaining robust design theory.

Defining and delimiting the perceptual approach to robust design introduced several limitations to the research. These limitations have entailed that only parts of much of the robust design theory used, have been relevant. Furthermore, given the applied limitations, often the theories used have been approached from a certain angle, which has influenced the interpretation. In many ways the common approach to robust design, where the objective performance of the product is the target for improvement, and the approach to perceptual robust design, is similar, but the systems to describe the dependencies are different. In particular, these differences pose new challenges when deriving the mathematical description of the dependencies, also referred to as the transfer functions.

Even though there are many approaches to robust design, it is a fairly well described field with well-defined tools and terms. Introducing the perceptual domain was less straight forward. The literature that came closest in terms of the use of perceptual theory was within the field of perceived quality. However, it did not fully provide the needed theoretical background to address the phenomenon in focus. For this the field of psychophysics provided a better basis. Rooted in psychology and neuroscience it investigates the relationship between physical stimuli and sensation and perception.

In the following sections key terms, methods, and theories that have been central to the conducted research is presented. First, theory related to product development is presented, which was important to understand how the contribution would fit in a larger context. Secondly, theory related to robust design is presented, which was central for the scoping of the research and in providing a basic understanding of the goal and means of robust design. Lastly, theory related to perceptual robust design is presented, which further helped scope the research and formed the basis for the proposed support.

3.2 Theory related to Product development

To position perceptual robust design in a larger context it was important to first understand the product development processes.

3.2.1 Design process theories

The design process can be approached in many different ways captured by a number of proposed models. The models offer structure and guidance to the design process, which often is a necessity in some form due to the complex nature of product design. Several authors have offered a categorisation for these design models. Some of the most commonly used categorisations are the stage-based vs activity-based models (Blessing 1994) and problem-oriented vs solution-oriented models (Lawson 2005; Birmingham et al. 1997). Furthermore, some design process theory focus on the design of mechanisms and product functions (Pahl & Beitz 1996), whereas others focus on the more managerial side of design (Hales 1993), including risk management (Baxter 1995). Most models and approaches acknowledge the relevance of the entire product development process in design, whether it is material costs or the cost of design iterations. Particularly, Ulrich and Eppinger (Ulrich & Eppinger 2003) addresses the complexity of the design process and argue that even the simplest design process is a highly complex socio-technical activity, which requires an understanding of a wide range of product related aspects.

What all design process theories have in common across the different categories is that they describe the steps to be taken in order to get from a problem or product idea to a complete design ready for production. Roughly, this also describes the common ground for different companies trying to develop a product. Diving further into the details of the design processes the best approach for a given company and product is highly individual. They all face different challenges and risks, and have different priorities and resources. Therefore, the design processes found with most companies will often be inspired by different models and approaches and formed by compromises and adaptions. However, some of the more abstract models, such as the Waterfall model or the V-model, seen in Fig. 8, are so general that they can be adapted to almost any requirements-driven development process without making compromises.

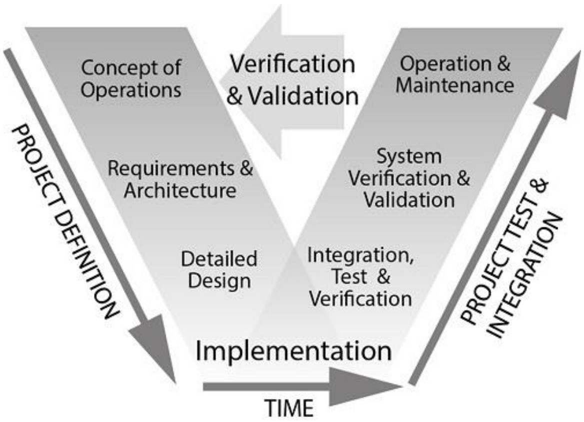

Figure 8. An example of a V-model describing the activities to be performed with the specification stream on the left side and the testing stream on the right side (Pandit & Thao 2015)**.**

Relevance:
Perceptual robust design is intended as a value adding approach in the larger context of product design. The models and systems used in industry determines when, where, and how new support can be implemented. This is crucial for developing the support and for estimating its potential value. Unless the proposed support offers value enough to justify changes in the design process, it should be able to merge with existing processes.

3.3 Theory related to robust design

For many companies, good quality management means controlling variation in production. However, engineering designers also plays a vital role in embedding quality into the design, through robust design methods. Robust design is used to ensure that product performance is insensitive to variation (Ebro et al. 2012; Ebro & Howard 2016). The research conducted as part of this thesis takes origin in the robust design theory. During the scoping of the research it has therefore been important to understand how perceptual robust design is positioned relative to the existing literature. Furthermore, in the development of the support, an understanding of the existing robust design tools and methods has been important to make use of them in the proposed support and to find inspiration in their current application. In the following, a short introduction to the most relevant robust design theory is presented.

3.3.1 The Taguchi Method

Robust design was originally introduced by Genichi Taguchi who proposed an approach known as the Taguchi method. The approach covers many aspects of product development and includes several analysis and synthesis methods, such as quality loss functions, signal-to-noise-ratios, and orthogonal arrays for use in design of experiment design studies. In short, the Taguchi method aims to improve the quality of conformance, that is, the ability of a product to meet its design requirements for the performance of the product (Taguchi 1986). The method employs robustness increasing strategies in three stages – system design, parameter design, and tolerance design (see Fig. 9). To address the challenges at each stage Taguchi developed a number of tool that have been widely implemented. Some of the most prominent have been the Taguchi QLF, the signal-to-noise-ratio, and the orthogonal array. The Taguchi QLF has been of particular relevance to this project and is describe in further detail in Section 3.3.3.

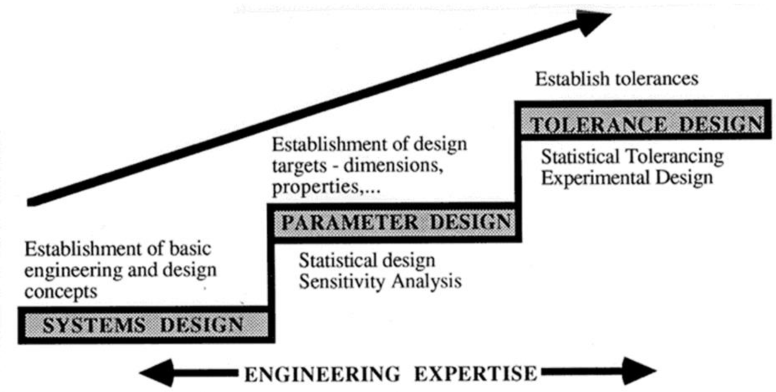

Figure 9. The three stages of the Taguchi Method – system design, parameter design, and tolerance design (WTec 1994)**.**

Since the introduction of the Taguchi method the field of robust design has evolved and many new methods and perspectives have been introduced. In (Suh 1990) Suh introduced his work on axiomatic design, which has since become a widely used approach in robust design. Several methods coming from the more general design theory has also found its use in robust design, such as design clarity, and basic tolerance chain analysis (Pahl & Beitz 1996). More recent contributions have introduced new optimisation tools and approaches (Yildiz 2013; Cheng et al. 2014; Wang et al. 2015). Furthermore, to support robust design methods and to visualise the effects, new contributions that build on the loss function theory originally introduced by Taguchi, have been proposed to optimise between multiple quality indicators (Hazrati-Marangaloo & Shahriari 2016; Soh et al. 2016).

Relevance to the research

As the Taguchi Method is considered the foundation for robust design it has been central for understanding the fundamentals of robust design. Additionally, many of the tools are still highly relevant and have been an important source of inspiration for the support presented in Section 4.

3.3.2 Transfer function

In engineering, transfer functions are mathematical functions that describe the relation between an input and an output. In different branches of engineering the inputs and outputs of transfer functions typically become more well-defined. In robust design a transfer function would typically describe the relationship between one or more DPs and the performance of a product function. This is illustrated in Fig. 10 where an arbitrary transfer function between one DP and the performance of a product function is shown. The dotted lines indicate the resulting functional performance given a certain value for the DP.

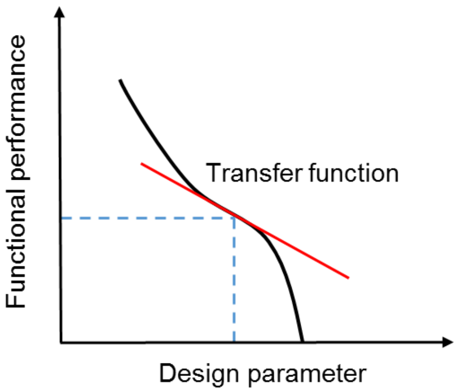

Figure 10. A transfer function between a design parameter and the performance of a product function.

Another term that is highly relevant to robust design and well described using transfer, is sensitivity. The sensitivity of the system is a measure of the change in functional performance given a change of the DP. If a relatively small change of a DP leads to a relatively large change in the functional performance, the system is said to be sensitive to variation. Likewise, if the opposite applies the system is said to be insensitive to variation, which is the definition of a robust design. Given a transfer function the sensitivity of a system can quite easily be determined as it is given by the derivative of the transfer function. Therefore, for a non-linear transfer function the sensitivity will change for different values of the DP. In other words, the sensitivity of a system for a given value of a DP equals the slope of the tangent to the transfer function at that given value (see Fig. 10).

In most practical situations a transfer function will have several inputs parameters, meaning the performance of a product function is depending on several DPs. For instance, the weight of a pen is not only a function of its length. It is a function of all the volumes and materials of the pen. Here the transfer function will be given by a multivariate function for which a partial differentiation will have to be performed to determine the sensitivity. If there are no interactions in the system the sensitivity can be derived much like for the univariate system. However, if the system involves multivariate interactions the sensitivity of one DP will depend on the value of other DPs. If interaction effects are deemed to be relatively small, estimates of the sensitivity of a DP can be found by keeping additional DPs constant, for instance, at their nominal value. Otherwise more sophisticated methods such as Monte Carlo analysis will have to be used to estimate sensitivity profiles.

Relevance to the research

The present research has focused on how product performance translate to product perception. For this QLFs have been used. However, in order to validate the support for making product perception more robust it was useful to trace design changes all the way back to DP level. To achieve this, transfer functions were derived based on DoE data and combined with models describing the perception of products.

3.3.3 Quality loss function

In the traditional understanding of product quality, a given functional requirement would at best have an ideal target along with an acceptable upper and/or lower allowable tolerance, and any performance within the tolerance limits was treated as being acceptable, or equally as good. The functional requirements could therefore be described with a step function as shown in Fig. 11a. Intuitively, however, if a certain function has a specification of e.g. 10 ± 1 N, it is in many cases irrational that an actual performance of 9.1 N or 10.9 N is equally good, whereas a performance of 11.1 N is unacceptable. Taguchi addressed this (Taguchi 1986) and presented the QLF, which is a more elaborate way of visualising the loss to society as a whole when the performance of a product function varies from its target. In Fig. 11b, an example of a QLF is shown. In both situations shown in Fig. 11 a nominal-the-best situation applies, as opposed to a smaller-the-better or larger-the-better situation. Comparing the step function to the QLF it is evident that significant quality loss occurs before the limits defined by the step function. It is not always possible to act on such information and limits might be chosen based on QLF information. However, awareness is always valuable and will ensure that better decisions are made.

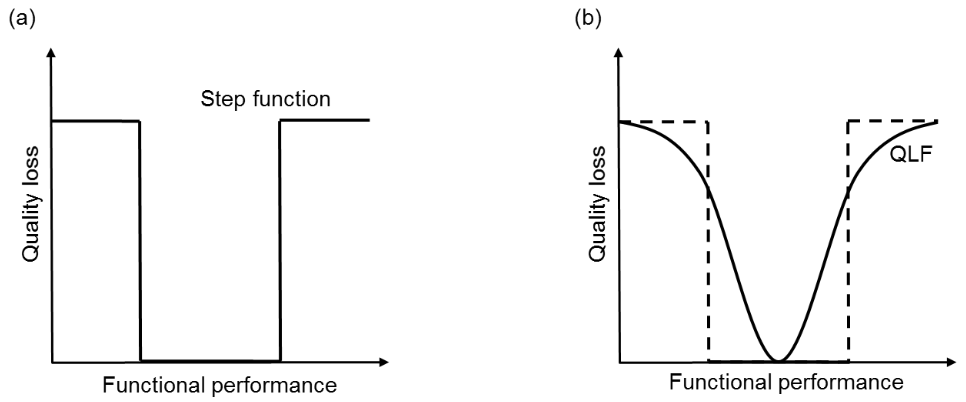

Figure 11. (a) Traditional requirements specification described as a step function (b) QLF based requirements specification.

Quality loss can be expressed in many ways. The theory behind the Taguchi QLFs operate with a definition of quality loss that relates quality to the monetary loss for the society as functionality moves away from the optimum. However, many other applications of QLFs have since been added to the literature. For instance, QLFs have already been proposed as a tool in a wide range of applications. Liao and Kao proposed the use of QLFs for selecting the optimal supplier (Liao & Kao 2010), Al-Me’raj, Cinar, and Duffuaa (Al-Me’raj et al. 2011) for determining optimal economic manufacturing quantity, Rahim and Tuffaha (Rahim & Tuffaha 2004) for determining optimal initial setting for process mean, and Hashemi, Ahmed, and Khan (Hashemi et al. 2014) for assessing process safety. These are just a few examples, but the idea of quantifying and continuously describing the correlation between input and output can be valuable in many situations. In product development the Taguchi QLFs have been discussed on a model basis in connection with Quality Function Deployment (QFD) by Bouchereau and Rowland (Bouchereau & Rowlands 2000), and as part of the Customer Optimized Design Analysis-system (CODA) – an enhancement tool for QFD (Eres et al. 2014; Woolley 2010).

Relevance to the research

QLFs is a central tool in the robust design theory. Particularly, in the assessment of the impact of robust design or when making optimisations based on quality related decision variables. With the present thesis focusing on the link between product and market, tools for quantifying the loss of quality is highly relevant. Therefore, QLFs have been used to design new support for the requirements specification process further described in Section 4.2.

3.4 Theory related to perceptual robust design

No consolidated body of theory related to perceptual robust design have been identified. However, much theory related to the topic exists, but within many different fields. Perceptual robustness is most frequently described in literature pertaining to compression algorithms and hash functions for image and audio files (Monga 2010; Yan Zhao et al. 2013; Kıvanç Mıhçak 2011; Karsh et al. 2016). This literature is of little relevance, as it differs in both scope and the use of perceptual models.

Perceptual robustness is also mentioned in literature addressing the robustness of multimodal interface design (Dumas et al. 2009; Oviatt 2003). However, this literature has a slightly different agenda as it focuses on the elimination of recognition uncertainty. Depending on the product functions in focus this could overlap with the issues usually addressed with robust design, but often the recognition of interface feedback would focus more on the cognitive processes than the sensory or perceptual processes.

The most relevant use of perceptual robust design was found in the perceived quality literature, which supported the argumentation for the relevance of perceptual robust design and helped scope the research. In addition the field of perceived quality introduces the notion of visual robustness (Forslund et al. 2006; Forslund 2008). Visual robustness have been defined as "(…) the ability of a product's visual appearance to stimulate the same visual product experiences as the nominal (perfect) design, despite small variation in its visual design properties" (Forslund 2008). This definition expresses the same goal as for perceptual robust design. However, the goal of perceptual robust design is to provide a basis that can be used across all sensory domains. Furthermore, the literature on visual robustness operates with more abstract models than those intended for perceptual robust design. Therefore the visual robustness literature has been considered a similar, but different approach to perceptual robust design, than the one presented in this thesis. To further elaborate on how the field of perceived quality has helped support and scope the research a more in depth overview is provided in the following.

To provide the theoretical basis for perceptual robust design the field of psychophysics was identified as the most relevant. Defined in the Encyclopaedia Britannica as the "(…) study of quantitative relations between psychological events and physical events or, more specifically, between sensations and the stimuli that produce them." (Encyclopedia Britannica 2005) it offers models to explain and predict how perception is affected by changing physical stimuli. Following the overview of relevant perceived quality literature, a more elaborate introduction to the field of psychophysics is provided.

3.4.1 Perceived quality

When dealing with perception in product development it is often in the form of perceived quality. This is probably the case as quality is directly or indirectly associated with the profitability of the product, which obviously is a great concern for many stakeholders. This relationship has been investigated in a number of papers looking at the link between perceived quality and KPIs more closely related to profitability, such as store traffic, or revenue growth (Babakus et al. 2004; Gotlieb et al. 1994; Rust et al. 1999). Many definitions of quality exist and several categorisations of quality can be found in the literature. In (Stylidis et al. 2015) an overview of some of the most cited contributions is presented mapping how these quality categories link and overlap. Common for all the authors included in this overview is that they operate with a perceived quality category. As highlighted by (Stylidis et al. 2015) and originally proposed by Garvin (Garvin 1984), quality can roughly be divided into two categories; the marketing oriented approach and the manufacturing oriented approach. The same goes for perceived quality, but with the manufacturing oriented approach heavily relying on physical and quantifiable measurements there is little need to concern oneself with the perception aspects. Thus, the marketing oriented approach, which to a wider extent includes subjective considerations, is where perceived quality finds the most relevance.

Looking into the components of perceived quality Forslund and Söderberg presents an overview in (Forslund 2008). The overview has its similarities to Lancaster's theory of consumer demand, where the perception of a product is described as the result of two elements - the objective characteristics of a product and the individual reaction to these characteristics (Lancaster 1966). Furthermore, Forslund and Söderberg's overview builds on Olson and Jacoby's differentiation between intrinsic quality cues, which are physical product characteristics, and extrinsic quality cues, which are non-physical product characteristics (Olson & Jacoby 1972). However, Forslund and Söderberg present the intrinsic quality cues as inputs for the quality appearance, which is again broken down into appearance design quality and appearance conformance quality. The appearance design quality describes the nominal design whereas the appearance conformance quality describes the conformance of products to the nominal design.

Another take on perceived quality is presented by David A. Aaker. In his book Managing Brand Equity, David A. Aaker (Aaker 1991) lists seven dimensions of perceived quality for products – performance, features, conformance with specifications, reliability, durability, serviceability, and fit and finish. All of these dimensions agree with the intrinsic quality cues as defined by Olson and Jacoby. Furthermore, Aaker's dimensions of quality also fit well with Forslund and Söderberg's differentiation between design quality and conformance quality. Particularly, the performance, conformance with specifications, reliability, durability, and fit and finish dimensions could be said to be related to Forslund's and Söderberg's conformance quality. It is therefore argued that products which are less sensitive to variation evoke a higher perception of conformance, which is directly correlated to higher levels of perceived quality.

When dealing with perceived quality it is important to differentiate between the pre-purchase and post-purchase product valuation as described in (Amini et al. 2014). The pre-purchase product valuation will usually be built on an immediate impression of the product in e.g. a supermarket environment. On the other hand, the post-purchase product evaluation, which becomes relevant for brand perception and repurchasing, will be based on the use of the product. Depending on the product, this use could be for an extended period of time or just a single use. In either case, the post-purchase evaluation will typically be based on far more product information, meaning that new features, functionalities, and details, including errors might be considered. This distinction is also addressed by Ophuis et. al. (Oude Ophuis & Van Trijp 1995) where intrinsic and extrinsic quality cues are defined as with Olson and Jacoby, but with the exception that experience quality attributes and credence quality attributes are introduced. Experience quality attributes are used to describe the quality attributes that can only be ascertained through experience with the product, such as taste or convenience. Credence quality attributes are attributes that are based on credence and which cannot be experienced, which would include healthfulness or animal friendliness. Therefore, according to the Ophuis and Trijp definitions, the pre-purchase product evaluation will be based on intrinsic and extrinsic quality cues, along with credence quality attributes, whereas the post-purchase product evaluation also will be based on the experience quality attributes.

The current practice among companies for applying perceived quality methods and approaches is hard to assess. For many companies it is the impression of the author that perceived quality is introduced implicitly as a part of voice of customers and product validation procedures. However, one industry distinguishes itself by having an open and well documented focus on perceived quality; and that is the automotive industry. Information concerning the perceived quality efforts of a number of car manufacturers is readily available online (Baker 2013; Tarmy 2014; Motor Corporation n.d.). A considerable concern for car manufacturers is the visual impression, and maybe in particular, the first hand impression. Here split lines obviously play a significant role but, also auditory and haptic product experiences are subject to perceived quality efforts. As a few examples, the sound of a car door closing, or the force profile experienced when activating the electric car door windows are areas where it is not obvious what users prefer and where significant perceived quality investigations have been conducted by companies.

Relevance to the research

The theory on perceived quality played a central role in the scoping of the present research. Furthermore, it has helped argue the link between perception of conformance and product quality and therefore also the relevance of perceptual robust design when it comes to product quality.

3.4.2 Psychophysics

The field of perceived quality is built on how humans perceive products. In general the perceived quality theory does not go into much detail with the biological, neurophysiological, and psychological explanations of the mechanisms of perception. However, these explanations are exactly what the field of psychophysics addresses. To explain the mechanisms of the human sensory-, perceptual-, and cognitive system, the field of psychophysics was introduced in the mid-19th century.

The processes of the mind can be investigated on three levels - low-level, mid-level, and high-level processes. In short, low-level processes can be described as sensory information gathering, mid-level processes as perceptual information synthesis, and high-level processes as memory and decision-making processes (Sarris 2006). With this definition of the processes of the mind, the research conducted as part of the present study has mostly been concerned with the low- and mid-level processes. That is, the processes that describe what happen between the emission of physical stimuli and the forming of a percept in the mind.

But what is human perception? In his book “Psychology” Harvard Professor Daniel Schacter defined perception as “the organization, identification, and interpretation of sensory information in order to represent and understand the environment” (Schacter et al. 2011). From the view of objective reality the process of perception is where the individual interpret the objective world and hereby creates a subjective understanding of it. To gather information about the external environment humans possess a sensory system. The information collected though the receptors, of the sensory system, is referred to as sensory information. This information is processed by the central nervous system to produce a percept of the external environment on which actions and decisions can be made to best serve an interest (Ernst & Bülthoff 2004; Kolb & Whishaw 2015). Assuming there is no bias in the processing of sensory information, accurate information will always be the best basis for taking the right actions. However, no sensory modality is perfect. Each of our senses can only capture information given by the physical stimulus that provokes a response from that specific type of sensory receptors. Depending on the situation this information is used to construct the most valuable percept given our limited processing power. For instance, in a well-lit room one would typically use the visual modality as the primary source of information when deciding the additional content in the room. However, if the light is turned off and the room turns pitch black no useful information can be obtained from the visual modality and other modalities, such as listening or touch, will have to be used instead. This weighting of sensory information is obviously very important in order to exclude biased or compromised information and combine information coming from several sensory modalities in the most efficient manner.

Some of the most commonly used measures in psychophysics are detection thresholds and difference thresholds. The detection threshold, which is also called the absolute threshold, is the threshold at which a stimulus can be perceived by the observer. For instance, the detection threshold of hearing is 20 μPa for a young person with normal hearing for a 1 kHz pure tone signal (Gelfand 2009). The difference threshold, also called the just noticeable difference (JND), is the threshold at which a change in the signal can be detected. Using the same example a JND of 1 Hz has been reported for changes in frequency of 1000 Hz signals (Kollmeier et al. 2008).

Relevance to the research

Psychophysics theory have been a central part of the theoretical basis for perceptual robust design. Most importantly, psychophysical models have been used to describe the relationship between product DPs and product perception. Furthermore, most available psychophysical data describe ideal circumstances with minimal noise and ideal stimuli. To collect more product related data, psychophysical methods and tools have proven highly applicable.

4 Results and discussion

In the following section the main results of the research conducted throughout the study is presented. The structure of the research, described in Section 2, was built around the research problems and the resulting research questions. The following section follows the same structure and is therefore divided into two main subsections – “Communicating robustness information”, and “Introducing perceptual robust design”. In the “Introducing perceptual robust design” subsection the research results have been further divided into the sections – “Theoretical basis for perceptual robust design” and “Practical implementation of perceptual robust design” to accommodate the division of contributions by each paper.

Each section introduces the relevant research question and briefly outlines the progression of the research and the common thread tying the research together. Following, details regarding the paper are presented along with a summary of the research results and a discussion of how it has helped answer the relevant research question(s). For information regarding how DRM stages have been addressed by the papers, see Fig. 7.

4.1 Communicating robustness information

In the research clarification it was established how perceptual robust design fits with the remaining robust design theory. Here, one particular challenge related to the VMF approach stood out; how to convert market quality loss information into useful design inputs. Having identified quality loss functions as a promising tool for expressing robustness information this representation still had to be integrated with industry product development practice to be useful. To address this problem, RQ1 was formulated as:

RQ1 – How can robustness information be better communicated between departments in the requirements specification phase?

To answer this question, potential means for communicating the impact of variation and sub-optimal design targets were investigated. The result was a new requirements specification tool called robust design requirements specification (RDRS) introduced in the following paper.

Paper title: Robust Design Requirements Specification: A Quantitative Method for Requirements Development Using Quality Loss Functions
Journal: Journal of Engineering Design
Contributor: First author
Status: Published
Appendix reference: Paper A

Summary of research results:
To address the identified problem of communicating robustness information in the requirements specification phase, the paper presents the RDRS method for quantifying early stage requirements. Furthermore, to substantiate the need and potential for utilising the approach the requirement completeness indicator (RCI) tool is introduced, providing an assessment of the level of quantification of a given requirements.

The RDRS method offers a new systematic way of quantifying and visualising product requirements, with a focus on quality loss. Given the use of quality loss functions, the method also provides the means to communicate robustness related information required to make design optimisations. The method consists of five principles (QLF, targets, limits, uncertainty, and variation), each chosen to address a key aspect of product requirements. Some of the principles are means of quantifying the requirement, whereas others provide valuable context to the quantification.

The use of quality loss functions is inspired by the use of quality loss functions in Taguchi theory. However, as the context of use is different the definition of quality is also different. Rather than looking at the monetary loss to society it is recommended that quality is defined in terms of the value to the user. Specifically, how to define "value to the user" will vary depending on the product, the company, and the market.

In Fig. 12, an RDRS visualisation of an arbitrary requirement with all principles applied is shown. The five principles are applied as follows.

QLF principle) The QLF principle is given by the curved graph and shows how quality loss changes as a function of the functional performance. An optimum is found at 10 N and moving away from this point will produce increasing quality loss. The curve was formed with shape-preserving interpolation using the MatLab Piecewise Cubic Hermite Interpolating Polynomial function.

Target principle) With basis in the QLF information a target is placed at 10 N.

Limits principle) Following, specification limits are placed at 6.5 and 15.5 N to reflect the decision of not marketing products with more than 35% quality loss.

Uncertainty principle) Throughout the product development process inputs will not always be perfect. Some are based on expert opinions, some on small user group investigations, some from previous studies related to other products. Regardless, it is important to know where the data is coming from when product decisions are made on basis of the information. As an example colour codes can be used. In this case the QLF data was coming from an individual estimate meaning it should only be used as a loose guideline. With this in mind it might be decided that better studies should be performed, or that other individual studies should be carried out to verify.

Variation principle) If there is data available on the expected variation for product function performance, optimisations can be run to minimise quality loss. In an ideal situation the variation can be described as a distribution in terms of type, mean, and standard deviation. However, often information will come from quality control of previous product lines and be limited to number of scrapped units. Assuming normal distribution and no mean shift this information can be used to compute the standard deviation. If measurement data is available on scrapped units even the mean shift can be computed. With estimates for the mean and standard deviation optimisations can be run using commercial software such as VarTran®. Fig. 12a shows target and limits before the application of the variation principle and Fig. 12b after.

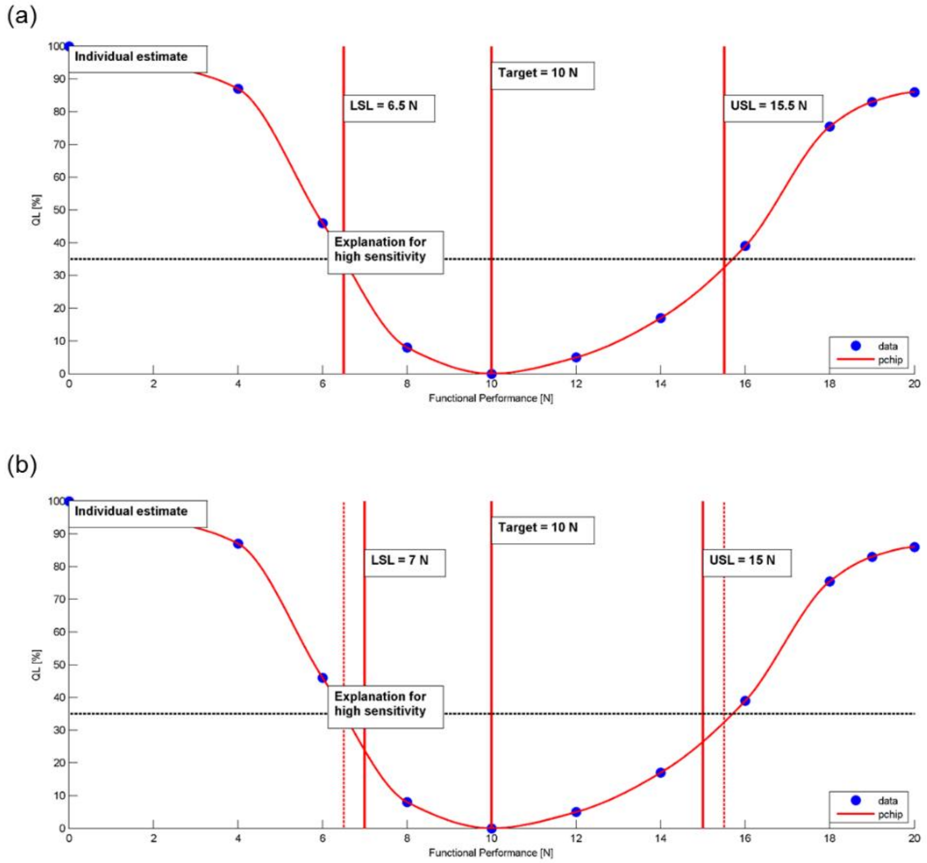

Figure 12. (a) A requirement with the QLF, target, limit, and uncertainty RDRS principles applied. (b) A requirement with all RDRS principles applied, where the limits before variation adjustments are shown with dotted lines.

To substantiate the need and potential for the RDRS an RCI case study was carried out. The RCI measured the potential for quantifying the 162 case study product requirements in terms of RDRS principles and the level to which this potential had been utilised.

As shown in Fig. 13, the results showed a considerable unutilised potential for quantification. 0% of the potential for applying the QLF and variation principle were utilised and only 10% for the uncertainty principle. Targets were applied for a little less than 30% and limits for around 70%.

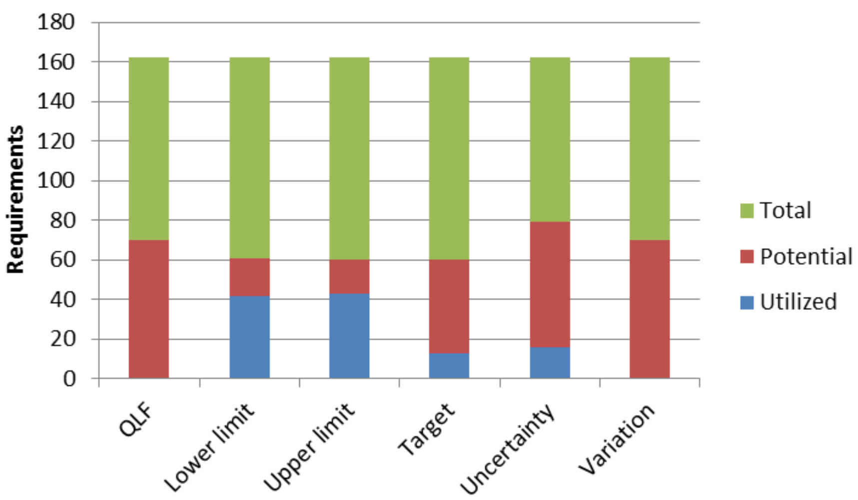

Figure 13. Results of RCI analysis showing the potential for applying the RDRS principles and how well the RDRS principles have been utilised.

Having verified the need and potential for the method the study went on to validate the applicability by applying RDRS to three product requirements from the case study. In each case it was possible to apply the RDRS principles and produce meaningful and information rich visualisation, similar to the one shown in Fig. 12. The usefulness of the approach was discussed on basis of a before-after comparison of the information included in the requirement. Further validation was omitted due to time constraints.

In conclusion the study proposed a new support for requirements development and showed that it was possible to communicate more exhaustive and useful information than originally provided by the requirement. Furthermore, the representative and meaningful visualisations produced in the case study served as a validation of the applicability and to some extent also the usefulness of the RDRS support.

Discussion of research results

With the objective of addressing RQ1, the results of the above paper will be discussed in the context of how well this objective was achieved.

RQ1 can be broken into several segments each of which had to be satisfied in order for the RQ1 to be fully answered. First, the overall goal of introducing better means for communicating product robustness information. Secondly, the means of communication had to be applicable for communication between departments, and lastly, the means of communication had to be applicable in the requirements specification phase.

Looking at the first part, five principles were proposed as the means for communicating robustness information. The central principle was the use of QLFs, with the additional four supporting the information held by the QLFs and providing actionable quantifications. The use of QLFs as a tool for communicating and quantifying the impact of non-compliance is widely recognised as part of the Taguchi theory. Many other contributions has since addressed the topic and showed how QLFs can be used for optimising designs for a minimal QL. The paper does not offer quantified validation of the effectiveness of the five principles for communicating robustness information. However, given the extensive and proven use of QLFs in the existing robust design literature it seems reasonable to state that they would provide effective means for communicating robustness information in the given context also.

As for the contextual requirements the product requirements documentation was chosen as the channel for communicating robustness information. Product requirements documentation is already used to pass information regarding product requirements between departments in the requirements specification phase why both contextual requirements is satisfied. Based on the case study examples of the paper, the applicability of the method was seamless and no obstacles were encountered.

With basis in the above considerations it is believed that despite requiring further validation the RDRS method offers better means for communicating robustness information between departments in the requirements specification phase. As such, the RDRS method has offered a qualified answer to RQ1.

4.2 Introducing perceptual robust design

With the proposed solution for improving the communication of robustness information, the problem of utilising perceptual theory for robustness in design was addressed.

The research conducted in relation to the problem was presented in two separate papers. Roughly, the first one sought to establish a theoretical basis and the second one to substantiate the support and validate the applicability and usefulness through a practical case study.

4.2.1 Theoretical basis

As a first step, in introducing perceptual robust design, state-of-the-art and current practice had to be investigated for perception based robustness research. This was captured by RQ2.

RQ2 – What is state-of-the-art and current practice for perceptual robustness?

Following, to further substantiate the idea of perceptual robust design, RQ3 addressed how to achieve it on a theoretical level and investigated the available necessary information.

RQ3 - What theories, metrics and data are available for designing perceptual robustness into products?

The results from the research motivated by RQ2 and RQ3 were gathered and presented in the following paper.

Paper title: Achieving a Robust Product Perception
Journal: Manuscript submitted for publication
Contributor: First author
Status: Manuscript submitted for publication
Appendix reference: Paper B

Summary of research results:
From a literature study conducted to answer RQ2 it was found that only little previous literature existed on the topic of perceptual robust design. However, a few related topics were well described, but still only sparsely in relation to robust design. The field that came closest was the field of perceived quality, approaching product quality from the perceptual side. With a strong focus on user

preferences, a considerable part of the field was not directly relevant, as preference and robustness often require different research approaches. However, the literature did provide the theory to establish a link between perceived quality and the robustness of products (Aaker 1991; Forslund 2008).

Visual robustness, also called visual sensitivity, was another topic closely related. Many of its applications have to do with image or audio hashing or compression, but it has also been used in the cross-section between robust design and perceived quality. In particular, it has been used in the automotive industry to optimise the design of split-lines. In this context the research has been presented as part of the perceived quality approach. This research was highly relevant to the present project.

In summary, the literature study showed that the level to which perceptual aspects of robustness are considered is very limited and highly industry dependent. Most commonly it was used for compression algorithms, where the premises are quite different from physical products. For use in design of physical products most existing research, approach the problem on a correlative level without diving into the underlying mechanisms of the forming of a percept. Furthermore, robustness considerations were only represented in very product and industry specific contexts. However, extensive research is available on the topic in the field of psychology and psychophysics, but these models have only been utilised in design to a very limited extent.

On basis of these results the perceptual robust design theory was now further substantiated by addressing RQ3. First step was to capture the motivation behind the approach. Following, second step was to further explore the field psychophysics, which had shown promising results in terms of quantified models for describing how perception is formed in the human mind. Then, last step was to present research findings and their relevance to robust design.

To summarise the motivation behind the approaching it was argued that the performance of a product often is defined as the objective performance, which leaves out an important aspect – the perception of the product. As a user of a product we are only aware of how we perceive the performance of the product. With a perceptual approach to robust design the bias and limitations of the human perceptual system, which can be described using psychophysics theory, could therefore be utilised to create more robust designs.

Exploring the field of psychophysics to identify useful theory describing the forming of human perception, a number of psychophysical laws and models were identified. Each of the laws and models used physical stimuli detectable by the human sensory system as input and some form of perceptual measure as output. The distinction between theory that was referred to as laws and models seemed to primarily be determined by how broadly they could be applied. In Table 1, an excerpt of the psychophysical laws and models presented in the paper is shown along with the pertaining mathematical expressions and examples of how they can be used to maximise robustness. For further elaboration on the expressions and robustness maximising strategies see Paper B.

Table 1. In the first column seven examples of psychophysical theory which can be used in perceptual robust design is presented. In the second column mathematical expressions pertaining to the theory is listed. In the third column examples of how the theory can be used to maximise robustness are given.

Psychophysical theory	Expression	Maximising robustness
Stevens' power law	$\psi(I) = kI^a$	$\min \frac{d\psi}{dI} = \min akI^{a-1}$
Weber's law	$\frac{\Delta I}{I} = k$	$\max \Delta I = \max kI$
Summation of the detectability of light	$T * I = C_{Bloch}$ $A * I = C_{Ricco}$ $\sqrt{A} * I = C_{Piper}$	Could be used in extension of detection threshold theory
Visual detectability of regularity	$p = g * W = g * \frac{1}{2 + N/R}$	$\min \left\lvert \frac{N}{R} - \frac{N}{R + \Delta R} \right\rvert$
Visual selective attention	No model available	Adjust perceptual load to maximise JND
Difference thresholds (colour example)	$ND(p,s) = p(A + \frac{B}{s})$	$\max p(A + \frac{B}{s})$
Detection thresholds	$I^{low.detect.lim.}$ $< I^{perceivable}$ $< I^{up.detect.lim.}$	Generate a signal outside of the perceivable region

For each law and model the application for perceptual robust design was discussed. In the cases where models were mathematically described, qualitative, and in some cases quantitative, strategies for controlling the perceptual sensitivity in design was described.

In summary the research showed that perceptual robust design is a novel approach to robust design. It is closely linked to perceived quality theory and in particular visual robust design, which could be said to be a subpart of perceptual robust design. However, with a basis in psychophysics theory perceptual robust design aims at a deeper understanding of the mechanisms of perception. Furthermore, it was shown that psychophysics can provide valuable inputs for producing perceptual robust designs.

In many ways these results are in line with a development seen in product development and marketing. With an increasingly better understanding of the human mind, the opportunities for utilising this information in product design opens up. In most contexts this information is of a correlative nature, as seen in much visual robustness literature. However, the psychophysical and neurophysiological field provides the means to form some understanding of the causality of the processes, which could lead to better models that require less empirical data. The perhaps strongest example of this development is the advent of neuromarketing, where users are no longer asked what they like, it is simply deduced from brain scans. The success of the approach speaks for itself, as several of the world's largest corporations are already making use of it (Burkitt 2009).

Discussion of research results

In the following, the extent to which the above research results provided an answer to the posed research question will be discussed. First, RQ 2 will be addressed, then RQ3.

To answer RQ2 a literature study was performed and experiences from external research in industry were analysed. The results of the literature study showed that the intended approach to robust design had only been introduced to a very limited extent in design. In other fields, such as computer science, a number of uses was found as well. It is hard to determine to what extent the literature study has been exhaustive in identifying all uses of a perceptual approach to robustness. However, the conclusions drawn from the literature found during the review can be discussed.

The paper concluded that perceptual robust design to a wide extent is a novel approach to robust design. Existing theory does touch upon the subject, but never goes into depth with it or provides a framework or basis for addressing relevant challenges or opportunities. As such, the state-of-the-art is fragmented and only applied in product specific contexts. Judging by the number of papers reviewed and their relevance and recency this conclusion seems reasonable.

As for current practice of perceptual robustness the best evidence was found in the marketing material of automotive companies. Based on these findings it seem likely that sophisticated methods related to perceptual robust design are being used in product specific contexts. However, with only a few documented cases this is largely speculative.

To answer RQ3, existing literature were reviewed focusing on its potential usefulness in design. Ideally such theory and data should offer quantitative models for the translation between the physical stimuli produced by products and the forming of a percept in the human mind. During the literature study, the field of psychophysics was found to offer exactly such models. In the paper, interpretations of psychophysical models are presented in regards to how they can be utilised in product design. Some interpretations resulted in quantitative models which could be used to describe the perceptual robustness, whereas others provided more of a qualitative input.

Again, it is hard to determine to what extent psychophysics covers all the relevant theory available. However, as a point of origin it has offered the necessary information to help design more perceptual robust products.

On basis of the overview of existing relevant literature and the presentation of robustness interpretations of psychophysical models, provided in the paper, qualified answers for RQ2 and RQ3 were provided.

4.2.2 Practical case study

Having formed a theoretical basis for perceptual robust design, the applicability and impact had to be validated. For this RQ4 was posed.

RQ4 - How can perceptual robustness theory be utilized in a product development context?

To address RQ4 a case study focusing on an injection device was performed to investigate the validity of the method in terms of applicability and usefulness. The results were presented in the paper Applying Perceptual Robust Design: A Case Study.

Paper title: Applying Perceptual Robust Design: A Case Study
Journal: Manuscript submitted for publication
Contributor: First author
Status: Manuscript submitted for publication
Appendix reference: Paper C

Summary of research results:
To show how perceptual robust design can be used in product design a case study was conducted. The case study looked at the loudness of a click sound produced by the dose dialling mechanism of an injection pen. Here the design of the mechanism was optimised for perceptual robustness in terms of the click sound loudness. Following, the benefits of the optimisation were evaluated on basis of the resulting potential for loosening requirements specifications for the click sound loudness.

To show how the design could be optimised two models were derived. First, a model to describe the translation between the perception of loudness and the actual sound pressure level (SPL) of a sound, and secondly, a model to describe the translation between the SPL of a sound and the DPs of a relevant click mechanism.

First, consulting the psychophysics literature it was found that the perception of loudness and the JND for loudness could be described using Stevens' power law and Weber's law, respectively. According to available data these laws indicated that the robustness of the loudness of a sound would increase as the SPL of the sound increases (Stevens 1957)(Teghtsoonian 1971). However, the data was based on pure tone signals rather than the broad spectrum of frequencies represented in a click sound. Furthermore, to be relevant in design the data would have to reflect the sound experience of actual use of the product, which would introduce some noise.

To verify that these findings based on existing psychophysics theory and data also held true for click sounds in an average use environment an experiment was conducted. The experiment investigated whether Weber's law, stating that the ratio between JND and a reference stimulus are constant, held true for the above conditions. In Fig. 14, the results from the experiment are shown. In total seven test subjects participated. Each participant were asked to judge whether a recording of a reference click and a following click where equally loud or of different loudness. The reference click were played at three different SPLs, shown by the three curves in Fig. 14. For each level the second click was amplified by 0, 3, 6, 9, or 12 dB and played in a random order with five playbacks for each amplification (difference level), meaning that 25 playbacks were played per reference level.

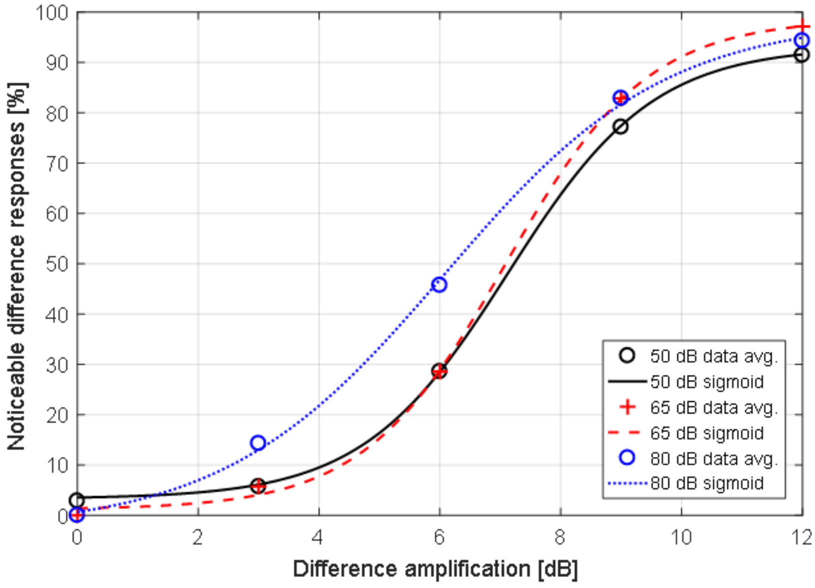

Figure 14. JND data for click sounds based on reference levels of 50, 65, and 80 dB SPL and difference levels of 0,3, 6, 9, and 12 dB.

The results showed that despite the JND being slighty higher at a reference level of 80 dB and difference levels of 3 and 6 dB, the difference was statistically insignificant with a p-value of 0.2. It could therefore be concluded that since the curves all follow the same path the ratio between the reference stimulus and the JND is constant and Weber's law holds true under the given circumstances. Hereby verifying that the robustness of the loudness of a sound would increase as the SPL of the sound increases.

Next step was to determine the translation between the SPL of clicks generated by a relevant click mechanism and the DPs of the click mechanism. To achieve this, data from a previous design of experiment study was used and new data presented along with a transfer model based on the data. In Table 2 the different DPs of the click mechanism is shown with estimates of the DP impact on SPL and the statistical significance of each parameter.

Table 2. Estimates, standard error, t-ratio, and prob(t) values for each chosen parameter and interaction.

Sorted Parameter Estimates				
Term	Estimate	Std Error	T Ratio	Prob>[t]
Arm width	1.1688905	0.051304	22.78	<0.0001
Arm height	4.2608361	0.285083	14.95	<0.0001
Body tooth height	2.3387773	0.159559	14.66	<0.0001
Gap	-3.839131	0.294153	-13.05	<0.0001
Arm length	-0.187436	0.015272	-12.27	<0.0001
(Gap-0.49521)* (Gap-0.49521)	-7.493183	1.003834	-7.46	<0.0001
(Body width-8.90411)*(Arm width-8.96804)	0.1190424	0.023072	5.16	<0.0001
(Arm length-49.3607)*(Arm height-2.49224)	-0.174448	0.037281	-4.68	<0.0001
Body width	-0.010009	0.052992	-0.19	0.8504

With basis in the derived models the design of the click mechanism was now optimised for maximum robustness. Three different optima were found and compared to the original design, first without constraints and since with constraints set at +/- 50% of the original design. The optimisations were performed using commercial software VarTran® with IT13 grade tolerances applied on basis of the original design. First optimum maximised the functional robustness, which was achieved by minimising the standard deviation of the transfer function between DPs and SPL of the click sound, also written as $\min \sigma(L(DPs))$. Second optimum maximised the perceptual robustness, which was found by maximising the SPL of the click sound, also written as $\max L(DPs)$. Last optimum combined the two by minimising the standard deviation of the composition of the two models, also written as $\min \sigma((\psi \circ L)(DPs))$. The added robustness for each design situation was assessed in terms of the potential for loosening requirements specifications. Here two different assumptions were made based on either Weber's law or Stevens' power law. The results are shown in Table 3.

Table 3. The impact of design situation 1-4, quantified in terms of potential for loosening requirement specifications with basis in assumptions of proportionality with Weber's law or Stevens' power law, shown in column three and five, respectively.

	JND (4% of L)	Δr_{new} for JND (%)	$\sigma(\psi)$	Δr_{new} for $\sigma(\psi)$ (%)
1) Original design	2.0248 dBA		0.05036	
2) $\min \sigma(L(DPs))$	2.2784 dBA	12.52-14.74%	0.044869 -0.045172	10.30-10.90%
3) $\max L(DPs)$	2.3232 dBA	14.74%	0.044869	10.90%
4) $\min \sigma((\psi \circ L)(DPs))$	2.3232 dBA	14.74%	0.044869	10.90%

Depending on method the potential was found to be either 10.9% or 14.74%. However, with a functional robustness optimisation introducing a potential of at least 10.3% and 12.52%, respectively, only 0.6% and 2.2% could be said solely to be achieved through an optimisation for perceptual robustness.

In summary, the research showed that for the case product it was possible to optimise towards a perceptual robust design in a meaningful way. As the case product design in many ways represents a very typical product design it is deemed reasonable to assume the same applicability would apply in many other cases. The usefulness of the perceptual robust design were quantified in terms of product requirement specification limits and showed promising results.

Discussion of research results

RQ4 raised the question of how perceptual robust design can be utilized in product design. This discussion will take basis in two identified requirements for answering the question. First the utilization of perceptual robust design, and secondly, the context of product design.

To accommodate the requirement for the product design context a case study focusing on design processes was chosen to address the question. The case study looked at a design that had already been through the design process, meaning the case study only retrospectively showed how the design could be optimised and did not have to deal with the challenges found in product design, such as design uncertainty and organisational and administrative processes and requirements. However, given the approach for optimising the design there was found no reason to believe it could not easily have been performed as part of the original design process.

To show the usefulness of perceptual robust design, the optimised designs were evaluated in terms of their potential for loosening requirements specifications. As mentioned in Section 2.4 this measure of usefulness was chosen as an indicator for a potential for increasing company profits. The line of argumentation is presented in Section 1.3.

In order to assess the potential for loosening the requirements specifications an assumption regarding the relationship between requirements specifications and the translation between perception and SPL had to be made. Actually, two assumptions were made. The first assumption was that the requirements specification for the click sound loudness was based on the perception of the loudness. The second assumption was that this dependency could be described as proportional to either Weber's law or Stevens' power law.

Starting with the first assumption, of course many considerations can influence the requirement specifications. However, often these considerations are related to the perception of the product if traced back far enough. Particularly, for the requirement used in this case study it seems reasonable to assume it was based primarily on perceptual considerations, as the loudness of a sound in itself is a perceptual phenomenon. As for the second assumption, it relies solely on the difference in approaches to the phenomenon of loudness. Weber's law is concerned with the JND, whereas Stevens' power law is concerned with the sensation magnitude. These two are closely linked, but not identical. They both represent proven quantifications of the translation between stimuli and perception, and as both seem to apply well to this case, they were both included. The difference produced by the assumptions was in this case up to 3.8% which is considerable, but did not make a difference for the conclusion of the study.

Many aspects of the perceptual robust design approach still needs validation, but on basis of the above discussion the presented research has shown how the approach can be utilised in product design and thereby offered a qualified answer to RQ4.

5 Conclusion

In the following section the conclusion of the project is presented. The conclusion is divided into several subsections. First, in the core contribution section the essence of the overall contribution is described. Then, the methodology used in the project is evaluated, followed by an evaluation of the research impact. Lastly, suggestions for further research are presented before the concluding remarks.

5.1 Core contribution

The main aim of this study was to add to the understanding and improvement of robust design theory, with a dedicated focus on the perceptual domain. With robust design being a subset of quality engineering, which again is an integral part of product development, the research intended to contribute not only to robust design, but also to the larger context of product development. The core contribution of this research is formed by the support and the insights produced, which can be summarised by the following contributions:

- Introduction of the RDRS method
- Validation of the applicability and usefulness of the RDRS method
- Introduction of the theoretical basis for the perceptual robust design approach
- Validation of the applicability and usefulness of the perceptual robust design approach

As given by the above points, the main support provided by this project consists of the RDRS method and the perceptual robust design approach. The introduction of the RDRS method was a contribution to the problem of communicating representative quality loss information as part of product requirements. This contribution merged existing requirements specification approaches with robust design theory, heavily inspired by the Taguchi method’s use of quality loss functions. In terms of validation, the applicability of the method was validated with case examples which showed that the technical aspects of the application could be easily implemented. The usefulness was validated in a before-after comparison of the amount of information captured in the requirement.

The introduction of the perceptual robust design approach was at the very core of the aim of the research. The contribution consisted of an outline of the theoretical basis and support for its implementation. In short it shows how the discipline of robust design can be merged with that of psychophysics, linking the forming of human perception all the way back to DPs.
To validate the applicability and usefulness and refine the method a case study was carried out. The case study showed that the approach by all means was applicable for the case study product and there were no indications of limitations to the approach. The usefulness was validated in terms of the quantified potential for loosening the product requirement specifications.

5.2 Evaluation of the research methodology

The chosen strategy and methodology for conducting the present research has largely been a success. The DRM approach provided structure and inspiration, not only for the type and content of studies to be conducted, but also the sequence.

In the research clarification stage the research was positioned relative to other approaches to robust design. Through this process the obstacles and challenges of communicating robustness information as part of the requirements specifications was identified and could be addressed.

The main challenge of the initial descriptive stage was identifying relevant research to help model the perceptual manifestation of products in a way that could be combined with robust design theory. Many fields, such as marketing, user research, etc., were consulted, and despite providing valuable inspiration and insights most of these fields were primarily focusing on preferences and usability. However, with the discovery of signal detection theory and psychophysics the right prerequisites for further substantiating perceptual robust design were found.

In the prescriptive stage appropriate support was presented. For the perceptual robust design approach this was a straight forward process given its intended role as defined in the VMF. However, only having validation data for the applicability and usefulness of the approach from a single case study it is likely that iterations of the prescriptive stage where the support would be refined on basis of case study data, would be beneficial.

The concluding descriptive stage was mostly used as a validation phase, as the nature of the support and the time constraints made a more extensive descriptive study unfeasible. However, using the concluding descriptive stage to consider options for validation and carry out the necessary research provided the means to draw preliminary conclusions regarding the applicability and usefulness of the support.

As shown in Fig. 7, all DRM stages have been covered for both of the addressed research problems. The thoroughness of each study, however, has varied depending on the requirements of the study set by the objective and the available resources.

In conclusion, the research methodology helped structure the research and ensured that all research questions were addressed and answered to a satisfying extent.

5.3 Evaluation of the research impact

The impact of the research can be divided into an academic impact and an industry impact. This distinction is often relevant for novel research as most industries will require a thorough validation before investing into an actual implementation. In small scales, industry case studies can be conducted, but as for the more theoretical case studies these will often only serve as an indicator of the potential impact. Therefore, the industry impact of the present research will be discussed in terms of its potential.

Starting with the academic impact of the present research, it can be approached from two angles:

1. The impact on robust design theory,
2. The growing utilisation of research explaining the processes of the human mind, including human behaviour, preferences, and, as in this case, perceptual capabilities.

First, looking at the impact on robust design theory. Inspired by existing and related theory, the present research have introduced a structured approach for evaluating and improving the perceptual robustness of all products functions that are perceived by customers. This opens up the opportunities for improving product robustness and hereby broadens the field of robust design, by means previously only represented in visual robustness literature. Furthermore, recognising the fundamental role of requirements in a data-driven product development process, the introduction of RDRS could serve as inspiration for further research into the prospects of including QLF based information as part of the product requirements.

As accounted for in Section 3.4.2 the research describing the processes of the human mind is being increasingly used to design and market products. The present research has taken another step to merge robust design with these new approaches, which undoubtedly holds a tremendous potential for improving product quality and customer satisfaction.

The industry impact of the research in its current form has been very limited as there have been no practical implementations of it. However, the research is believed to hold a potential for making more perceptual robust products, which has been quantified in terms of the potential for loosening requirement specifications. However, more robust products will not only allow for looser tolerances, potentially generating significant cost savings, it could just as well be used for improving the perceived quality of products, which is also closely linked to product profitability.

5.4 Suggestions for further research

With the introduction of perceptual robust design a first step for consolidating perceptual research related to robust design has been taken. However, much research remains to be done to fully establish the field of perceptual robust design. In the following, suggestions for further research are described. Some suggestions are directly related to the present research and covers areas that were not fully addressed due to time constraints. The remaining suggestions are research opportunities which were revealed throughout the project.

RDRS case studies

Having introduced the RDRS method, three case study examples where the method was applied were presented. The examples showed, that for the chosen requirements the method was easily applied and by comparing before and after information it was argued that a more complete set of information was presented using the RDRS method. However, requirements vary significantly in detail and content of quantified information. Therefore, additional studies to show a broader applicability of the RDRS method would be a valuable support of the validation. Furthermore, the usefulness of the method should be validated in real development projects, where the completeness of information and the potential benefits of it can be evaluated qualitatively through interviews, or quantitatively by measuring relevant indicators. Such indicators could be design iterations, prototyping costs, or overall profitability of the project.

Perceptual robust design case studies

With the injection pen click sound case study, some initial validation of the applicability and usefulness of the perceptual robust design approach was presented. However, theoretically the potential of perceptual robust design will vary considerably between products and product functions. Additional case studies should be carried out to improve and validate the application of the approach, and to investigate patterns in potentials for usefulness. In the case study presented in this thesis the usefulness was quantified in terms of the potential for loosening requirement specifications. As this approach proved to be successful, it could serve as a good basis for comparison between studies.

Consolidate relevant psychophysics theory
Much of the research related to psychophysics is labelled under other terms more specific to the sensory domain it focuses on, or to the medical or biological field related to the sensory system. This has been an obstacle during the literature review and much research still needs to be done in order to create a full overview of the psychophysical models currently available. Creating such an overview could provide design engineers with a broad palette of models to describe the link between DPs and product perception and make appropriate optimisations.

Multimodal studies
Most product functions are perceived through several sensory modalities. Understanding how these modalities support or mask each other in different product use situations would help make even more perceptual robust designs. Theory describing the phenomenon already exists to some extent. Two ways of addressing this research would be to gather existing literature with a focus on robust design relevance and collecting new data, using existing psychophysical experimental approaches.

5.5 Concluding remarks

This study has been an inspiring and eye opening journey into the field of product development, robust design, and the human mind. Embarking on a three year project and seeing it through has been a tremendous personal and professional challenge that has given me many valuable experiences.

I find the prospects of merging engineering design with sciences of the human mind to be truly inspiring. With this thesis I hope, not only to have made a small contribution to the field of robust design, but also to have taken a step towards a better utilisation of new and existing human perceptual theory, in the development of new products.

6 References

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7 Core papers

Paper A.	Robust Design Requirements Specification: A Quantitative Method for Requirements Development Using Quality Loss Functions Pedersen, S. N., Christensen, M. E., & Howard, T. J. (2016). *Journal of Engineering Design*
Paper B.	Achieving a Robust Product Perception Pedersen, S. N. & Howard, T. J. (2017). Manuscript submitted for publication (*Design Studies*)
Paper C.	Applying Perceptual Robust Design: A Case Study Pedersen, S. N. & Howard, T. J. (2017). Manuscript submitted for publication (*Journal of Engineering Design*)

JOURNAL OF ENGINEERING DESIGN, 2016
http://dx.doi.org/10.1080/09544828.2016.1183163

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Robust design requirements specification: a quantitative method for requirements development using quality loss functions

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ABSTRACT
Product requirements serve many purposes in the product development process. Most importantly, they are meant to capture and facilitate product goals and acceptance criteria, as defined by stakeholders. Accurately communicating stakeholder goals and acceptance criteria can be challenging and more often than not, requirements will be subject to simplification, causing ambiguity and uncertainty, with negative consequences for the company and the users. To prevent such incidences, a new approach for creating more complete requirements is proposed in this article. Grounded in robust design theory, the approach uses quality loss functions as one of the five principles, to visualise a more complete set of requirement information in a single figure. In order to validate the potential and applicability of the proposed approach, a new indicator for requirement completeness is introduced, expressing how open the requirements are for interpretation. By applying the method and indicator to a case study from the medical device industry, it was found that less than 45% of the potential for quantification had been utilised. Finally, the robust design requirements specification method was successfully applied to three case study requirements, to illustrate the gains in terms of the level of quantification, transparency, and comprehensiveness of the provided information.

ARTICLE HISTORY
Received 22 May 2015
Revised 19 April 2016
Accepted 23 April 2016

KEYWORDS
Risk and reliability; quality issues; taguchi methods; customer satisfaction

1. Introduction

In the early design phases product requirements are often expressed as stakeholder requirements (or needs) and are since translated into functional requirements. In an attempt to assess the level of quantification of product requirements in a large medical device company a case study was conducted (see Section 5). The study looked at the company's product requirement documentation from project initiation to final production. Through analysis of one of the company's most recent projects a considerable unutilised potential for quantifying requirements was identified.

The reasons for not quantitatively describing product requirements are many – while some do not have the information to be specific in their requirements, others are concerned they will restrict the design engineers and therefore avoid being too specific. For

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instance, at present the design engineer takes the requirements specifications as a set of hard targets, even though the relevance and uncertainty of the specifications might vary considerably. This can easily cause problems later in the design process, which is one of the reasons why quantified information often is left out. Taking specifications as hard targets in the early design phase can be problematic as the context always adds essential information. For instance, a user satisfaction optimum might be identified for a certain design, but introducing small design changes later on can change this optimum. Therefore, quantified requirement specifications must be accompanied by transparency and traceability. A transparent requirement is defined as a requirement where the reasoning, the context, and all related assumptions are clear to the reader. Likewise a traceable requirement is defined as a requirement where all sources and associated requirements are clearly stated.

The goal is not to provide comprehensive validation for every requirement, but to represent each requirement in a complete way, which better communicates the rationale behind specifications to the design team and thereby allows us to use quantified information when communicating requirements. In other words the goal is to turn the ‘unknown unknowns’ into ‘known unknowns’ and maybe even into ‘known knowns’.

Obtaining quantified information from stakeholders and turning it into useful information for the design team can be a challenge. However, a number of methods for feeding stakeholder inputs into the product development process have already been proposed. For instance, existing literature provides numerous methods for translation of user requirements into functional product requirements, often build around the principles of Quality Function Deployment (QFD) (Hauser and Clausing 1988; Zhou 1998; Tontini 2007; Xiong, Yu, and Wang 2014). Some have worked with the communication of user inputs via visualisation tools (Jermakovics et al. 2007; Guzman, Bhuvanagiri, and Bruegge 2014), or used visualisation tools to improve the traceability of information in product development (Martinec and Pavkovic 2014). However, not much has been written about the communication of the outputs and how to include sensitivity analysis to better anticipate stakeholder responses to variation. As addressed by Krogstie, Ebro, and Howard (2014) the substantial cost of poor quality in product performance, often arising from variation, is a key motivation for implementing variation management systems, such as robust design. That is, a design where the product’s functional performance is insensitive to variation, for example, in part dimensions. In other words, a robust design will have little change in the functional performance of the product when, for example, variation in part dimensions is introduced. Thus, it is important to set robust targets and limits to mitigate or avoid quality loss arising from variation. In the robust design literature this is also known as parameter optimisation (Ebro and Howard 2016).

In this article a new approach for quantifying early stage requirements will be presented and discussed. For the remainder of the article this approach will be referred to as Robust Design Requirements Specification (RDRS). Along with the RDRS approach an analysis tool for assessing the potential for implementing RDRS for a set of requirements will be introduced. This analysis tool will be referred to as the Requirement Completeness Indicator (RCI). The main focus of the RDRS approach will be on a new innovative use of Quality Loss Functions (QLFs) originally introduced by Genichi Taguchi in the field of tolerance analysis (Taguchi and Clausing 1990). Inspired by these ideas loss functions are integrated to provide a better understanding of the implications of design decisions, such as varying functional targets in early product requirements. In addition, a further quantification of product requirements will provide more unambiguous and clear-cut product requirements, potentially reducing product development-time and costs.

In a case study the RCI analysis will be performed on a set of requirements followed by the application of RDRS on several of these requirements to assess the potential and applicability of the tool. The assessment will focus on whether or not the tools add useful information for the design team and to what extent it is possible and useful to quantify requirements.

2. Background

For many years product requirements and QLFs have existed as separate fields of research. In the following, a brief overview of previous work in the field of product requirements and QLFs is presented. The overview will serve to underpin the novelty of the approach proposed in this article while introducing key terms.

2.1. Product requirements

A considerable number of academic proposals have dealt with the development and management of product requirements. Darlington and Culley (2002) offered an exhaustive overview of the state of the art research in engineering design requirements. However, none of the contributions concerned itself with the introduction of QLFs as a mean to describe requirements. Since then many contributions have added to the field. Cui and Paige (2012) proposed a framework for aligning requirements with business motivations, where they made use of network models and matrices to map out and validate connections and completeness. In another contribution they targeted business strategy as a driver for requirements development (Cui and Paige 2014). Others have focused on stakeholder driven requirements (Decker et al. 2007; Wu, Ding, and Luo 2014) or strategies for the requirements management process (Hauksdóttir and Nielsen 2014). In addition, several standards from the International Organization for Standardization (ISO) also address this topic (Schneider and Berenbach 2013). The majority of these approaches target software development, but several also cover systems or product requirements. Typically, the process described in standards will include a stakeholder analysis where stakeholder needs are documented and processed, followed by the actual requirements development process where the requirements are formulated (Chrissis, Konrak, and Shrum 2006; ISO/IEC/IEEE 2011). Despite the many contributions in the field of systems engineering in recent years the use of QLFs in requirements development has still not been utilised as a visualisation tool.

For the purpose of this article the focus will be limited to stakeholder and functional product requirements. The documentation describing these requirements will be referred to as the Product Profile (PP) and Product Specifications (PS), respectively, as used by the case company of this study.

A PP is a 'solution-neutral' way of describing the purpose and intended use scenarios of the product that is intended to meet the stakeholder needs. As an example, the PP of a novel medical device could describe the general functionality of the product in terms such as: 'The product can deliver a dose size from 1 to 20 units' or 'The product should be more discreet than existing solutions.'

A PS, as described by Pahl et al. (2007) is a tabular collection of the product's requirements that can also refer to solution specific requirements, such as 'The torque to activate the dose button is 1 Nm ± 0.1 Nm.' The target value of the specification can be one of three types (Taguchi 1986):

(1) Smaller the better, such as 'dose inaccuracy', where there is no lower specification limit (LSL).
(2) Larger the better, such as 'user dismantling force of a disposable device', which should not be dismantled and hence has no upper specification limit (USL).
(3) Nominal the better, such as 'dose activation force' where, for example, a button has an ideal target value.

Apart from describing the target value, the acceptable USL and LSL are described. For 'nominal the better' the limits can be described with the target as a reference point '1 Nm ± 0.1 Nm' or without referencing a target '9.9–10.1 Nm'. For 'smaller/larger the better' it is implied that the optimal target will be 0 or infinity and therefore LSLs and USLs, respectively, are not meaningful. As a consequence 'smaller/larger is better' is often only described by an USL or a LSL, respectively. In this regard it should be noted that in practice a requirement only described by a single limit does not automatically imply a 'smaller/larger the better' situation. For instance, a product specification might set an USL of 30 N motivated by safety regulations. In this case a 'nominal the better' situation for the optimal user satisfaction could very well apply.

The information provided in the PS, as described above, states only hard targets and limits, which are often simplifications. For compliance with standards and regulatory requirements these hard targets are often sufficient, but when dealing with customer and user satisfaction such simplifications can introduce significant quality loss. The current alternative of only adding qualitative targets or limits provides very little information and leaves room for ambiguity and miscommunication, which can lead to inefficiencies in the development process. Therefore, there is a need for a better way of integrating quantified information into product requirements.

2.2. Taguchi quality loss functions

In the traditional understanding of product quality, a given functional requirement would at best have an ideal target along with an acceptable upper and/or lower allowable tolerance, and any performance within the tolerance limits was treated as being acceptable, or equally as good. Intuitively, however, if a certain function has a specification of, for example, 10 ± 1 N, it is in many cases irrational that an actual performance of 9.1 or 10.9 N is equally good, whereas a performance of 11.1 N is unacceptable. Taguchi addressed this (Taguchi 1986) and presented the QLF, which is a more elaborate way of visualising the loss to society as a whole when the performance of a product function varies from its target.

Quality loss can be expressed in many ways. The theory behind the Taguchi QLFs operates with a definition of quality loss that relates quality to the monetary loss for the society as functionality moves away from the optimum. For the purpose of this article this definition will not be adapted. Instead focus will be on the features of the QLF itself and quality will be described as a potential on an abstract scale.

The QLF provides the designer with continuous information about the functional performance instead of just for a target and maybe some limits. Consequently, it is possible to express the sensitivity of a function performance as the derivative of the QLF – a steep gradient indicates a large change in quality for a small change in performance. This can be utilised both ways, meaning that the sensitivity can be derived from a quality loss curve fitted to a data-set or used as input information when intuitively describing the QLF.

QLFs have already been proposed as a tool in a wide range of applications. Liao and Kao proposed the use of QLFs for selecting the optimal supplier (Liao and Kao 2009), Al-Me'raj, Cinar, and Duffuaa (2011) for determining optimal economic manufacturing quantity, Rahim and Tuffaha (2004) for determing optimal initial setting for process mean, and Hashemi, Ahmed, and Khan (2014) for assessing process safety. These are just a few examples, but the idea of quantifying and continuously describing the correlation between input and output can be valuable in many situations.

In product development the Taguchi QLFs have been discussed on a model basis in connection with QFD by Bouchereau and Rowlands (2000), and as part of the Customer Optimized Design Analysis-system (CODA) – an enhancement tool for QFD (Woolley, Scanlan, and Eveson 2001; Eres et al. 2014). However, whereas Bouchereau and Rowlands (2000), Eres et al. (2014), and Woolley et al. (2001) deals with ways of improving QFD by combining it with the Taguchi Method and CODA, respectively, this contribution focuses on the communication and completeness of product requirements. Therefore, the methods should be viewed as complimentary rather than competing.

3. Robust design requirements specification

The RDRS method offers a new perspective on quantified product requirements and a systematic approach for assigning and visualising critical values for functional requirements. Hereby, communicating the desired product qualities clearly, and in a form that makes it easier to make optimal design decisions. The method consists of five principles (QLF, targets, limits, uncertainty, and variation) each described in the following sections. Each of these five principles was chosen to address a key aspect of product requirements, which would benefit from visualisations. A total of five principles were chosen to provide a sufficient set of information. QLFs, uncertainty, and variation can here be viewed as explanatory principles guiding the setting of targets and limits. The core of the approach is the introduction of QLFs to illustrate the impact of design decisions. However, the uncertainty of the QLF and variation introduced in, for example, production can significantly impact how the QLF should be used for setting targets and limits and must therefore also be considered. Thus, the five principles are meant to collectively cover all vital information to consider when setting targets and limits for a product function.

The RDRS method does not include basic requirements management systems. Instead it should be regarded as a supporting tool for developing and presenting complete requirements and their underlying data. Here, it is important to mention that RDRS does not assist in the acquisition of quantified data. Rather the method encourages a data-driven requirements development and helps structure, visualise, and communicate the information. Likewise, the method will not define to which extent quantified information is needed. However, by clearly visualising the information available, RDRS will help design engineers and managers assess whether or not additional information is required. In some cases expert opinions might suffice for validating the requirements, in other cases thorough market studies must be conducted.

In the following sections descriptions of RDRS principles are presented, supported by RDRS visualisations. These visualisations are intended to help the reader realise how RDRS can help convey more accurate and complete requirements information.

3.1. Quality loss function

The method is based on an adaption and extension of the Taguchi QLF, where the broad spectrum of information QLFs provide is utilised to communicate trends and sensitivity profiles in addition to specific values of interest. The QLF describes how customer satisfaction correlates to the performance of a product function for which functional requirements are required.

A part of the adaption from the Taguchi method is an alternative definition of quality. Originally Taguchi defined quality in monetary terms as the value to society in its whole (Taguchi 1986). As RDRS is meant to be a communication tool, the information in the QLFs must be well defined. Therefore, the definition of quality used in RDRS is reduced simply to the value to 'the user', where 'the user' is to be defined by the company. For instance, it might be a weighted average of a certain composition of market segments. This allows for a direct translation between user studies and QLFs, which is important for validating early stage assumptions regarding user satisfaction and reactions to changes in product performance.

In order to normalise the quality loss (QL) scale, estimates and user data are converted into a percentage scale going from 0% to 100%. The maximum user satisfaction in the explored solution space will be the reference point with 0% QL whereas the minimum user satisfaction will define the 100% QL. The conversion scale is therefore determined by the maximum and minimum of the observed values and the reference will be the best score. This means that QL should be thought of as QL compared to the optimum. Consequently, a given amount of QL for certain vital functions may have a larger impact on the overall user satisfaction compared to less vital functions. In other words, the QL for a given function does not provide a basis for comparison between product functions, only a basis for assessing the performance and potential of the given function. However, special events and a description of severity can be added as part of the annotations described in Section 3.4. The functional range in which the QLF is described depends on the interests of the design engineers. Often data will only exist for a limited range around an estimated optimum.

The context in which the quality loss is evaluated is also important as there can be interaction effects between product functions that affect the user experience. Typically, the context would be as mature as the function to be tested, meaning that in the early design stages it would be on a conceptual level. As the design matures so will the context in which the quality loss is evaluated. It is therefore important to re-evaluate quality loss when the context changes in ways that are expected to influence the output and to state the context associated to a QLF. As an example the development team might want to test how user satisfaction correlates with the force required to open a screw lid on a bottle, so they produce a prototype to represent the conceptual design. At a later point the design has changed considerably. The diameter of the bottle has increased, the material is smoother, and the lid is flatter. This has a significant impact on the grip of the bottle and the lid, which very well could mean that users would prefer a smaller opening force. This shows how reusing outdated data can result in suboptimal or even detrimental requirements specifications, which is why all specifications must be transparent and traceable.

One of the great advantages of the QLF is that it can present valuable information that is important to the design engineers, in one figure. It can provide an explanation for targets and limits, and show where one might expect design pitfalls, represented by a steep gradient of the curve, also referred to as high sensitivity. Some product functions might have a wide optimal plateau revealing that it will have little impact if the functional performance varies. In other situations it might be a matter of drastic quality decrease and exceeding limits can cause catastrophic product malfunctions resulting in extensive costs for users and the company. Examples of functional performance addressed by product requirements could be the force to open screw lid of soda bottle, the push distance of a car's start button, the power-up time for a laptop, or any other functional aspect of a product.

The QLF can be derived in several ways resulting in different levels of uncertainty. Preferably the QLF should be based on extensive and relevant data. However, as resources typically are limited, often the QLF would be based on limited data or more or less qualified estimates, in which case the QLF simply could be drawn by hand. The deduction of QLFs in general will not be discussed further in this article. However, the uncertainty linked to the sources of the derived QLF will be addressed. In Figure 1 it is shown how a QLF derived from a limited number of data points could look like. In the examples presented in this article shape-preserving interpolation has been used to derive the curve between averages of the QL for the investigated levels, using the Matlab Piecewise Cubic Hermite Interpolating Polynomial function. In Figure 1 the interpolation was based on fictitious data from 12 performance levels for the force required to open the screw lid of a bottle. The 12 performance levels range from 0 to 20 N and their corresponding QL values are the normalised values of a quantitative user survey. For instance, test subjects might rank the performance from 1 to 10 with 10 being the best. In this example 10 N might have scored 8 and 0 N scored

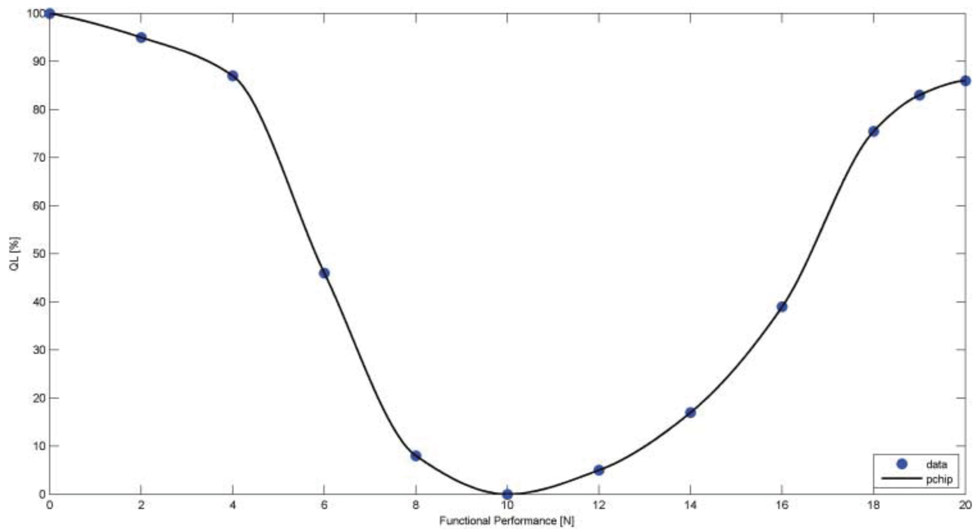

Figure 1. QLF derived by shape-preserving interpolation for data from 12 performance levels.

0, with all other levels being in between the two. Normalising this ranking, 100% QL corresponds to 0 N and 0% QL corresponds to 10 N. Depending on the expected variation and approximate knowledge of user satisfaction optima, the range of functional performance can often be limited to a narrower interval, as it is known that, for example, 0 N will be an unacceptable solution.

As an example of how to read Figure 1 it can be seen that for an opening force (functional performance) of 16 N the average test subject experienced approximately a 40% QL compared to the best ranked opening force of 10 N. As often seen for nominal the best situations the QLF follow an inverse bell curve, also known as a well curve. Mathematically this form can be described as an inverted exponential function composed with a concave quadratic function. However, these functions do not allow for many of the irregularities seen in Figure 1, which is why shape-preserving interpolation has been used here.

3.2. Targets

Having derived a QLF for the product function, the design engineer can start considering an optimal target. Several considerations should be made before choosing a target. First of all, the purpose is to minimise the loss of quality, which relates directly to the minimum of the QLF. Next, variation must be considered, for instance arising from manufacturing or assembly. Lastly, cost considerations can be included in the later design stages for optimising the profitability or the life-cycle costs of the product. Production, assembly, supplier, distribution, and sales capabilities are just a few examples of cost-associated considerations that might influence an optimal product function target. However, for the purpose of this article cost optimisation will not be described in further detail.

Based on the QLF presented in Figure 1 one might choose a target of 10 N, indicated by the vertical line, corresponding to the optimal QL (see Figure 2(a)).

3.3. Limits

Setting limits can be crucial for success as limits can reflect decisive turning-points for the functionality of the product or acceptance criteria for regulatory authorities. As with targets, the design engineer needs to consider factors like variation and cost when deciding on limits. With access to the information given by the QLF it is possible to define limits according to acceptable quality loss, if there are no other obvious limitations. Again, one could make use of analytical tools to incorporate variations in the calculations of limits that correspond to a certain quality loss or make estimates. In the example 35% quality loss was chosen as the limit to avoid the steepest parts of the QLF while keeping the QL on a reasonable level. From the intersection of the horizontal line at 35% QL it appears that 35% QL approximately corresponds to a LSL of 6.5 N and an USL of 15.5 N. In the figure indicated by vertical lines (see Figure 2(b)). Had there been any external or internal standards providing limits these would have been added also.

3.4. Uncertainty

In order to clearly communicate the level of uncertainty that applies to a quantified requirement, it is important that the information behind is transparent and the sources are

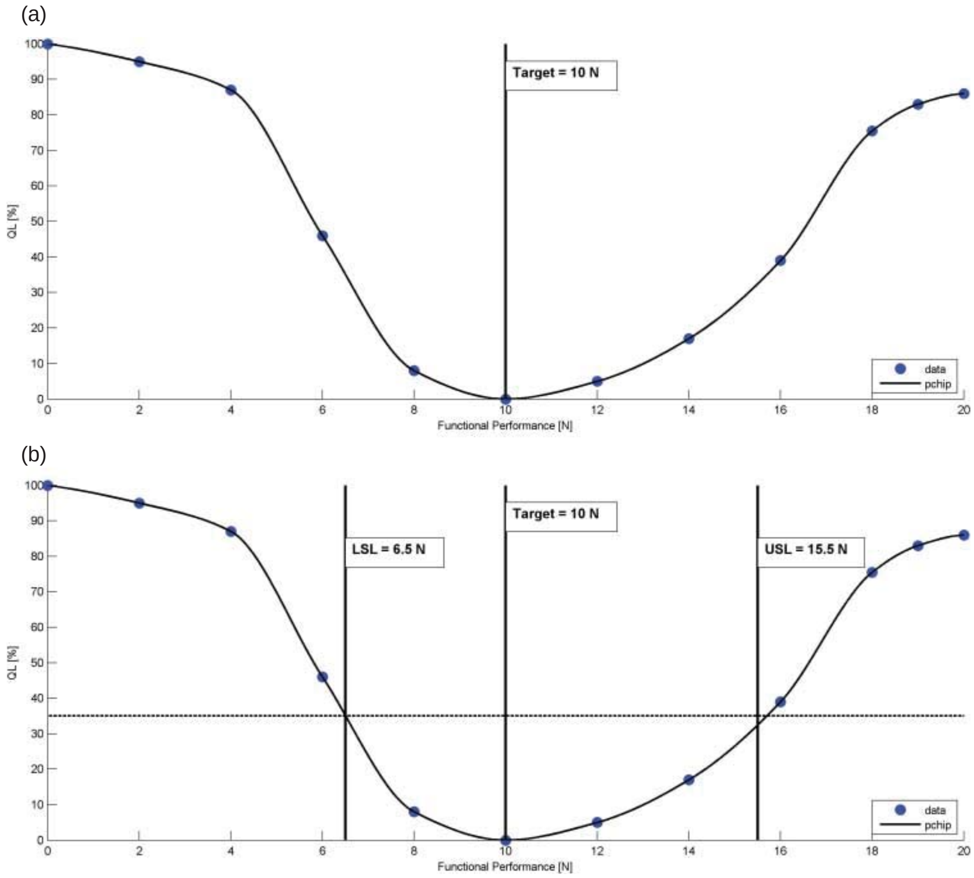

Figure 2. (a) A target is chosen for the optimal QL. Here at 10 N. (b) Having decided that the maximum acceptable QL is 35% lower- and upper specification limits are placed at 6.5 N and 15.5 N, respectively.

Table 1. Colour code categories.

Colour codes	Uncertainty category
Black	Strict goal or limits
Yellow	Flexible guideline
Red	Loose guideline

traceable. Simply stating the sources can lead to quite a detective work going through documentation, therefore two simple steps for providing a more sufficient transparency and traceability are introduced. First, a line colour code to indicate the level of uncertainty and consequently how strict the requirement is. This colour code applies to the QLF as well as targets and limits. For quick referencing, uncertainty has here been divided into three categories as shown in Table 1 – strict goals or limits, flexible guidelines, and loose guidelines. Secondly, the option of adding annotations to points of interest, for example, describing the source of the QLF, the reasoning behind targets or limits, or explanations for drastic sensitivity changes, such as critical changes in product performance. Together with the colour codes, these annotations provide a quick and easy overview of the background of the requirements. These tools should be used as an add-on for existing requirements management systems documenting and back-tracking requirements. In Table 1 the colour code used to symbolise different categories in the following examples are specified.

These categories should be customised to fit the design routines and needs of the individual company or department. The important part is that the design engineer gets a quick overview of the requirement and instantly knows if targets or limits should be considered loose guidelines or strict goals or limitations. The difference typically being whether the information comes from an individual guess for an early design or statistical significant data from user studies performed on a mature design.

In this example the QLF was derived based on an individual estimate meaning the QLF is subject to considerable uncertainty, and one should therefore use a red line colour. As the target and limits are solely based on the QLF these are likewise considered loose guidelines. The annotation 'Individual estimate' is added to clearly communicate the source of the uncertainty along with an annotation explaining the steep curve that are seen below 7 N. The result is shown in Figure 3(a).

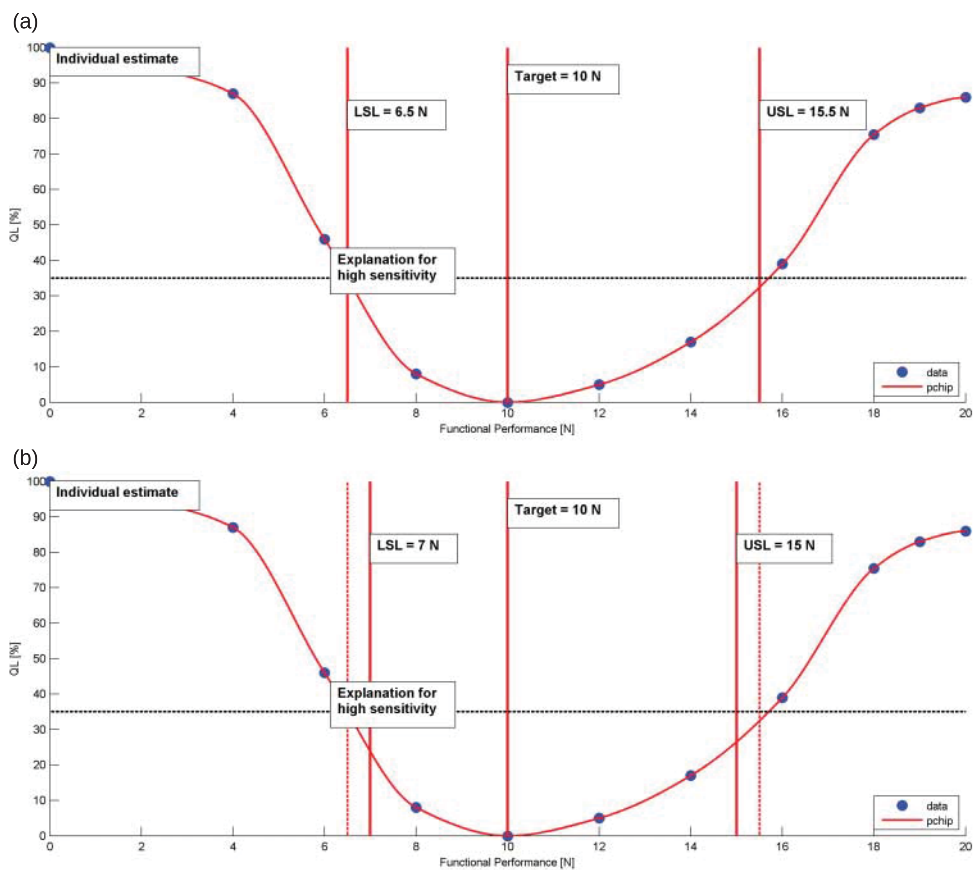

Figure 3. (a) By adding annotations and colouring the QLF, the limits, and the targets red, the source, points of interest and the overall uncertainty of the requirement is made clear to the design engineer. (b) Shifting target and limits to mitigate QL related to estimated or known variation coming from, for example, manufacturing.

3.5. Variation

Because the world is inherently stochastic, product performance varies from the specifications. Therefore, it can be useful to anticipate these variations by adjusting targets and limits so that the average product performs optimally.

In the early design stages many of the sources of variation are not yet known and quantifying variation will therefore be based on a 'black box' estimate. At later stages the variation can be statistically approximated, which in the production domain often is expressed in Six Sigma terminology as a defects per million (dpm)-value (Westgard 2006). However, variation can originate from many sources. The areas where variation that influences functionality usually would be seen are manufacturing, assembly, load, and time (Christensen, Howard, and Rasmussen 2012).

Including variation in the target setting means that if the QLF has a high sensitivity on one side of the target and a low sensitivity on the other side, the target should be shifted towards the less sensitive region to optimise for minimum quality loss. Likewise, when determining limits variation should be considered and limits adjusted accordingly. To do so first acceptance criteria for the variation must be established. If detailed knowledge of the variation and QL is available it could be limits for spread, form, and location of the product performance distribution. If only sparse data is available, the variation acceptance criteria could be limited to just stating a maximum number of units performing outside of the product performance limits. In the example a simple variation acceptance criteria could be a maximum of 10 products out of a million performing below 7 N or above 15.5 N, which corresponds to the performance limits of 35% QL. Based on the expected variation and the variation acceptance criteria, targets and limits can now be adjusted.

Including variation requirements in the product requirements should reduce firefighting in production and avoid sudden functional drop-out of loss of performance of products. However, for the purpose of this article specification of variation will not be described in further detail. Therefore, even though variation considerations will be included in the examples they will only be used as 'black box' estimates.

Applying these variation considerations to the example, the target is shifted towards the insensitive region right of the optimum and the limits are put closer to the target. How big a buffer that is needed depends on the estimated variation, the sensitivity of the QLF, and the variation acceptance criteria. In this example it is estimated that 0.5 N will be a sufficient buffer for both LSL and USL, resulting in a LSL of 6 N and a USL of 15 N, see Figure 3(b).

4. Requirements completeness indicator

Before apllying the RDRS method it is important to benchmark the current levels of requirements quantification to assess the scope for improvement. To achieve this the RCI analysis is proposed, to be applied to a PS from a case study. According to the RDRS principles, for completeness a requirement would need to contain information related to a QLF (or similar quantified sensitivity estimates), LSL, USL, target, uncertainty, and considerations related to variation. The RCI sums the number of RDRS principles present in each requirement, which gives an indication as to how complete (or vague) a requirements specification is. Requirements which cannot be expressed via any of these principles are deemed unfit

Table 2. RCI analysis table for the five versions of the milk carton requirement.

Req. name	QLF	Lower limits	Upper limit	Target	Uncertainty	Variation
1	0	n/a	0	1	0	0
2	0	n/a	1	1	0	0
3	0	n/a	1	1	0	1
4	1	n/a	1	1	1	1
5	n/a	n/a	n/a	n/a	n/a	n/a

Notes: n/a indicates that the requirement is unfit for RDRS quantification, a 0 indicates an unutilised potential, and a 1 indicates a utilised potential.

for RDRS quantification. For most part, such requirements will be non-functional requirements, which in the field of systems engineering are also referred to as 'quality attributes' or 'constraints' (Stellman and Greene 2005). To be able to recognise when only a single limit is used in 'nominal the best' cases the 'limit' principle is divided into two test parameters – USL and LSL. Each requirement is rated for each RDRS principle. If the principle is exhibited within the requirement is scores a 1, if it is missing it, it scores a 0, and for instances where that particular RDRS principle is not applicable, it is notated by 'n/a' (e.g. the USL for a larger the better requirement would therefore be n/a).

To illustrate the methodology the following examples will show how the RCI analysis captures the level of quantification in a requirement for a milk carton.

Consider the following five versions of a milk carton requirement:

(1) 'The carton should be able to contain milk without leaking.'

Here we are presented with a smaller the better situation, implicitly stating that our target is 0% leakage and that lower limits are not applicable (n/a). However, the requirement does hold a potential for quantification in all categories, as evident from the following versions of the requirement (see Table 2).

(2) 'The carton should be able to contain 1 L of milk without leaking more than 1 mL per day.'

Here an upper limit has been introduced (see Table 2).

(3) 'The carton should be able to contain 1 L of milk with a maximum of 1 in 1000 cartons leaking more than 1 mL per day.'

Introducing variation considerations it is acknowledged that there will be a variation in the performance of the product, which is included in the requirement (see Table 2).

(4) 'The carton should be able to contain 1 L of milk with a maximum of 1 in 1000 cartons leaking more than 1 mL per day. With a p-value of 0.08 obtained from a small user study ($n = 25$) it has been established that user satisfaction decreases following the equation $2.45y^2$ moving away from zero leakage.'

Here QLF and uncertainty information is included in written form. The QLF information is given by the equation describing the decrease in user satisfaction and the uncertainty is given by a short description of the study and the resulting p-value (see Table 2).

These are examples of how information similar to that of the RDRS principles could look. However, the form and level of detail can vary, especially for the QLF, uncertainty, and variation.

Not all requirements are fit for quantification. Staying with the milk carton example, an unfit requirement could look like the following.

(5) 'The carton must have labelling complying with the (EU) 1169/2011 regulative.'

In this case the requirement is compliance related and non-functional with no potential for quantification (see Table 2).

The authors believe that the RCI is useful for gauging the potential for improvement and clarification, but it could also be a useful comparative indicator between projects within a company.

5. Case study

As previously mentioned, the case study took place at a larger medical device company focusing on a product that had been recently marketed at the time of the study. The study focused on the Product Specification (PS) listing all the product's requirements. The PS held 162 requirements which were analysed using the RCI. This PS was the final version of the document before the project had moved to production. Due to confidentiality reasons further details surrounding the company, the product, and the PS have been limited.

The case study included an RCI analysis of the PS requirements and the application of RDRS on three modified example requirements.

5.1. RCI analysis

The RCI analysis was carried out as prescribed in Section 4 for each of the 162 requirements found in the case product PS and the analysis was performed by one of the authors and a research assistant.

During the RCI analysis it was found that a considerable proportion of the requirements were unfit for being quantified. Furthermore, it was found that there had been no attempt to describe the requirements in ways that might resemble QLFs and neither had there been added any considerations regarding variations among requirements. Transparency was lacking, with only 10% of the requirements having clear references or sources stated, despite a considerable potential for adding this information. The same applied for targets, where less than 30% of the quantifiable requirements had defined targets. The results are summarised in Figure 4 and further discussed in Section 6.1.

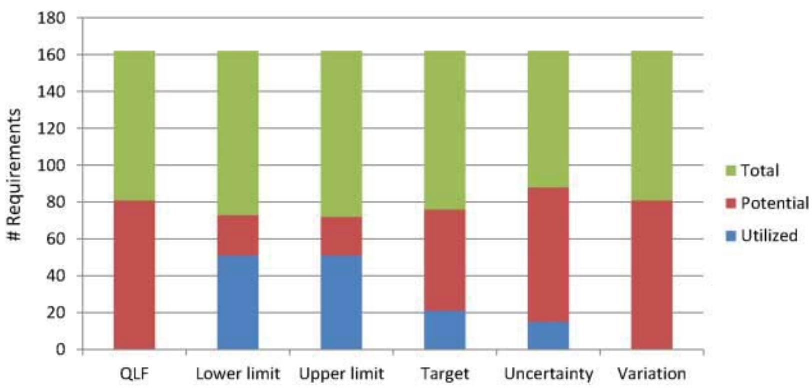

Figure 4. Results of RCI analysis showing the potential for applying the RDRS principles and how well the RDRS principles have been utilised.

To validate the categorisation (measurement system) and investigate the operator to operator variance, an analysis of variance method called Attribute Gage R&R analysis was performed on the two operators (author and research assistant) with the categorisation results used as reference. The result of the attribute Gage R&R analysis was an overall effectiveness of 91.3%. According to Automotive Industry Action Group (AIAG) guidelines for process variation, a leading authority in Attribute Gage R&R analysis, an overall process effectiveness of 90% or more can be described as a 'good process'. Thus, the resulting variation of the categorisation process was considered acceptable (AIAG 2002).

The above results show that there is a large potential for further quantification of requirements. In order to test whether the RDRS method can be used in a practical way to increase this level of quantification, three example requirements are modified and further quantified using the approach.

5.2. RDRS Example 1

In this example the requirement is formulated as follows:

'Force to put on cap: Maximum 30 N.'

There is no information regarding sources or previous use of the requirement.

This is a fairly simple requirement with an USL and no LSL or target. From the information given in the requirement it is not possible to make any uncertainty estimates. With no assessment of uncertainty the requirement could be visualised in its original form as shown in Figure 5.

As is evident from the figure, this does not present much information or provide much guidance for the design team.

By interviewing members of the team which developed the product, it was determined that the requirement had been based on studies carried out internally in the design team.

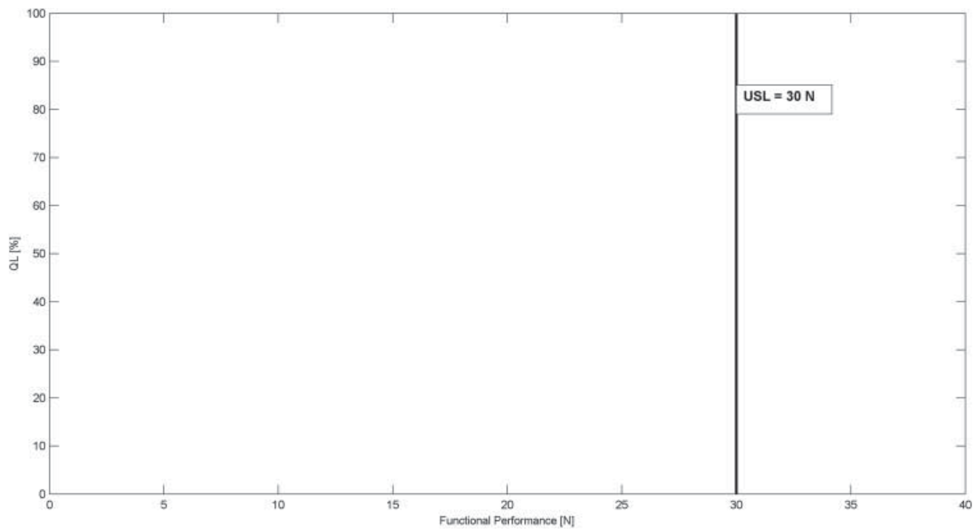

Figure 5. Visualising information given for Example 1 requirement.

Therefore, the data behind the requirement is subject to some uncertainty and one should only use it as a flexible guideline.

Applying the RDRS method we start out by estimating a QLF. In this example the estimation will be a team estimate obtained by investigating the force required in previous products and producing nine different prototypes that require from 0 to 40 N to put on cap. Noting down each team members ranking of the prototypes, an average for each level is found. Due to the degree of uncertainty the QLF will only apply as a loose guideline. A loose guideline could, for instance, be seen as an approximate target knowing that it might change later on. The alternative here would often be no information at all. Instead the design engineer now has a guideline with the necessary information for making the right choices. The resulting QLF could look like the one shown in Figure 6, derived using shape-preserving interpolation for nine data points.

The QLFs in Figure 6 show that we have a fairly large plateau going from approximately 18–28 N with a maximum of 10% quality loss. As the old USL was based on team estimates for another product, it can be assumed that considerable uncertainty applies to the value of 30 N and it is therefore used as a loose guideline. This allows for an adjustment of the limits, which are then changed to keep the functional performance within the identified plateau, corresponding to a maximum of 10% quality loss. Furthermore, 25 N is identified as the optimum and therefore used as the target. To adjust for the expected variation, the LSL is set at 18.5 N and the USL, which lies in a more sensitive region, is set at 27 N. The result is illustrated in Figure 7, where red line colour is used to indicate that the QLF is based on a project estimate. As targets and limits are derived from the QLF these are also based on a team estimate.

Here the design engineer has a complete overview of the user response to his or her design decisions. Of course these are only estimates and should only be used as such, until the values have been further validated through user studies.

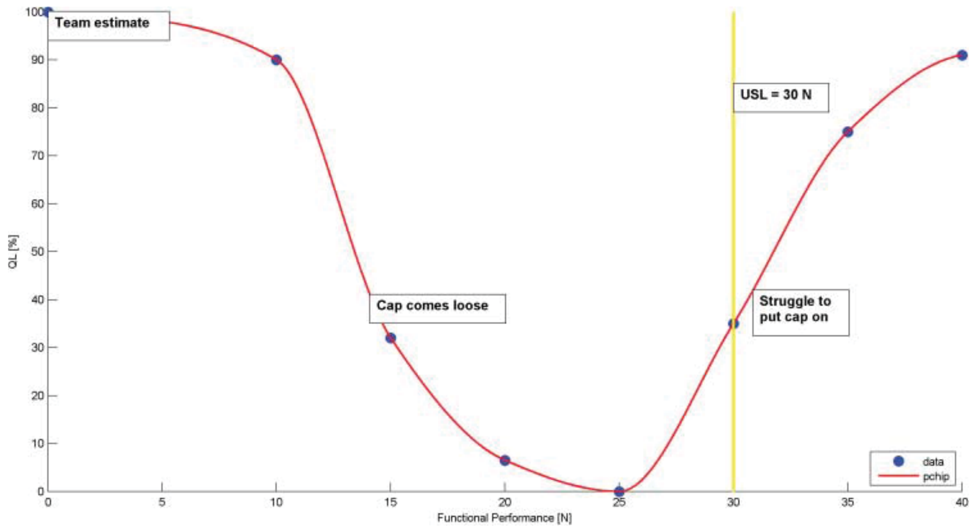

Figure 6. QLF derived by shape-preserving interpolation for Example 1 data.

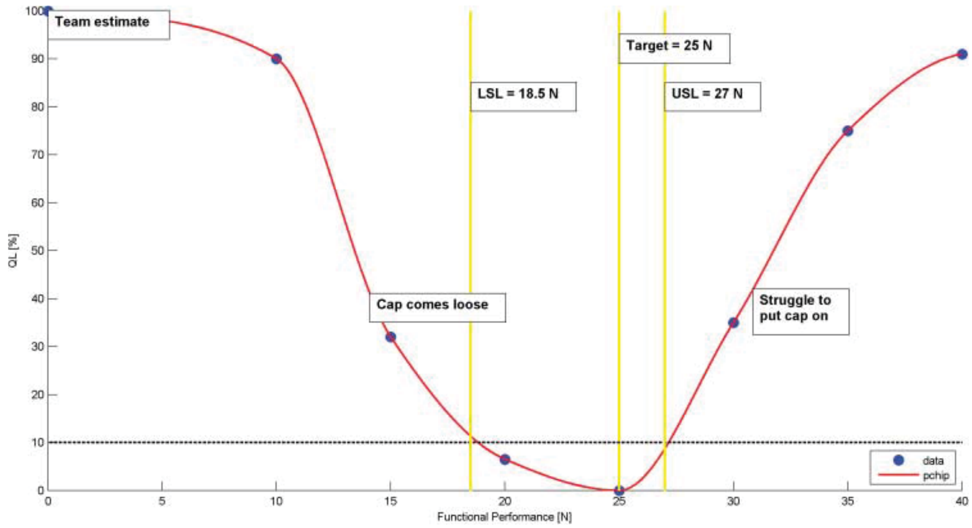

Figure 7. Example 1 requirement described using RDRS.

In this case a further validation of the QLF would mean that the large plateau going between the LSL and USL could be utilised and the tolerances loosened without experiencing any significant QL, hereby reducing costs.

5.3. RDRS Example 2

The second example has more information. The requirement states:

'U10 dosage requirements from ISO standard: Maximum 10 ± 1U.'

The requirement states that choosing a dose of 10 units the delivered dose may not deviate from 10 units with more than one unit. Here, a target, an USL, a LSL, and a reference to an ISO standard are included in the requirement. As these targets and limits are set by standards there is assigned no uncertainty.

In this example more information is given with a target and both an USL and a LSL, as shown in Figure 8. What we do not have is an overview of the quality loss that occurs between these limits. Does the target fit with the quality loss optimum and how will deviation from the optimum affect quality loss? For this example it is that data from a number of user studies or controlled clinical experiments, exploring user satisfaction at seven different levels, has been collected. From the data, a QLF has been derived by use of shape-preserving interpolation between seven data points. The resulting curve is due to the extensive data, assumed to have very little uncertainty, and can therefore be used for choosing strict goals and limits, as shown in Figure 9.

In the figure it can be seen that if the dose gets larger than the optimum there is a drastic quality loss compared to administering a smaller dose. As the gained user satisfaction is expected to outweigh the costs of tightening tolerances an USL of 10.5 units is added, corresponding to the same quality loss as the LSL, namely 37.5%. As very little variation is expected for this product function, no corrections for targets or limits are added.

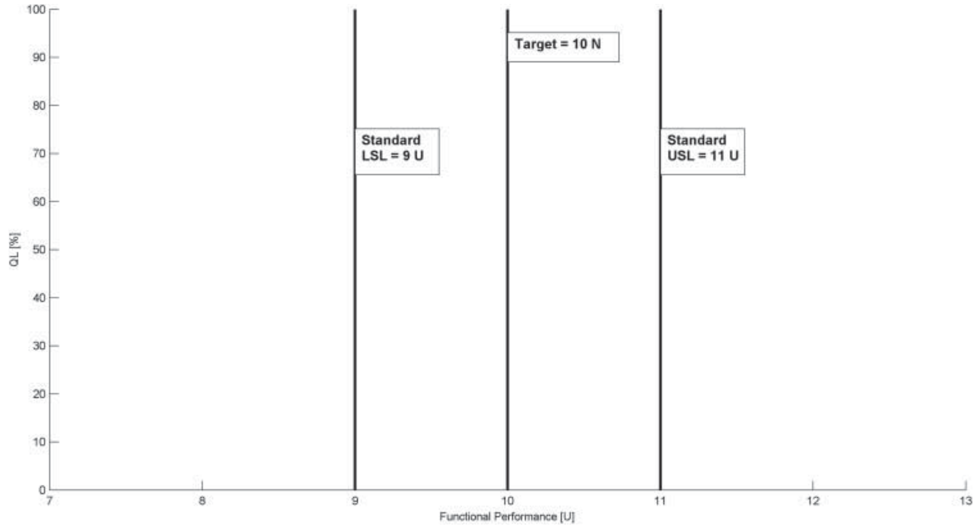

Figure 8. Visualising information given for Example 2 requirement.

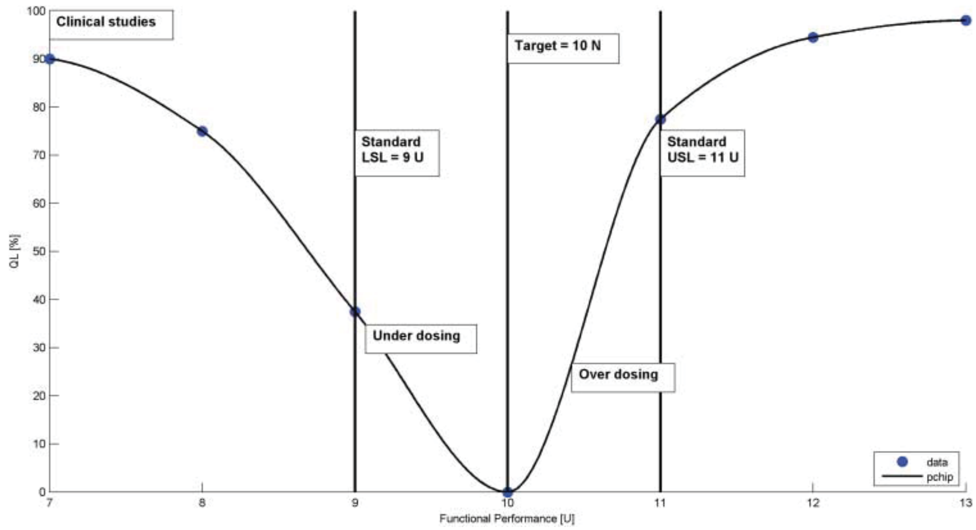

Figure 9. QLF derived by shape-preserving interpolation for Example 2 data.

Once again, far more information is available, as shown in Figure 10, which gives a more complete overview of the impact of design decisions. By introducing a new USL and tightening tolerances accordingly QL can be reduced to half of what we had before. Of course, the profitability of such a manoeuvre would heavily depend on the production process capabilities.

In the following example the focus will be on a requirement, which has not been quantified. The RDRS method will be applied to show how it could be quantified.

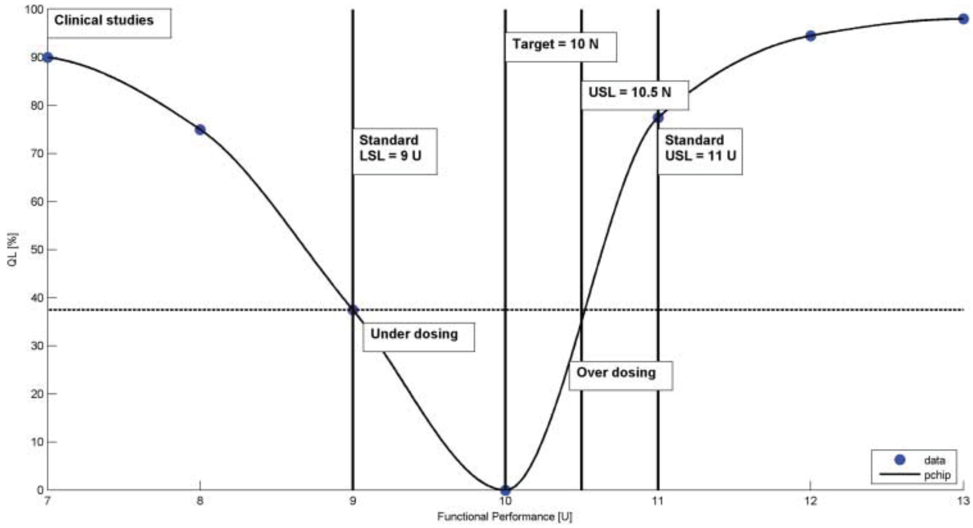

Figure 10. Example 2 requirement described using RDRS.

5.4. RDRS Example 3

In this example a qualitatively described requirement, modified from an ISO standard prescribing that clicks must be 'audible'. The modified requirement reads as follows:

'Audible clicks during use: Audible in a silent room.'

Before the quantification of the qualitatively described requirement can start, the meaning of the requirement must be clarified. What is meant by 'audible' and 'silent room'? In practise these questions should be answered by sound specialists, the internal marketing department, and the development team. For the purpose of this article 'audible' will be interpreted as audible for the 90th percentile of the best hearing users and 'silent room' will be defined as 30 dB sound pressure level white background noise. For simplicity it is assumed that click sounds considered for the product are similar enough in frequency composition, that it can be assumed that the click will be audible at the same level for all click sounds. In Figure 11 the audibility threshold in a silent room is plotted for the 90th percentile of users. The value is based on a scientific study conducted by the company and it is therefore assumed to be accurate enough for use as a strict lower standard limit.

However, this only tells how to comply with the standard. Customer quality needs might be even more demanding and varied. Some prefer loud sounds as it makes them feel more secure while others prefer discreteness and less distinguishable sounds. Exploring the relationship between quality and loudness of the sound through a smaller user study looking at eight different levels could produce a QLF as the one shown in Figure 12. In this example it is assumed that some uncertainty applies to the QLF and it is therefore only used as a flexible guideline.

Next, target and limits can be chosen based on the QLF. As very little variation is expected the target is at the optimum of the QLF. Furthermore, a maximum of 20% QL is chosen for the limits, resulting in a LSL of 40 dB and an USL of 60 dB, as shown in Figure 13.

First of all, a quantified and validated interpretation of the qualitatively described requirement from the standard will be applicable for future use as well. Hereby the

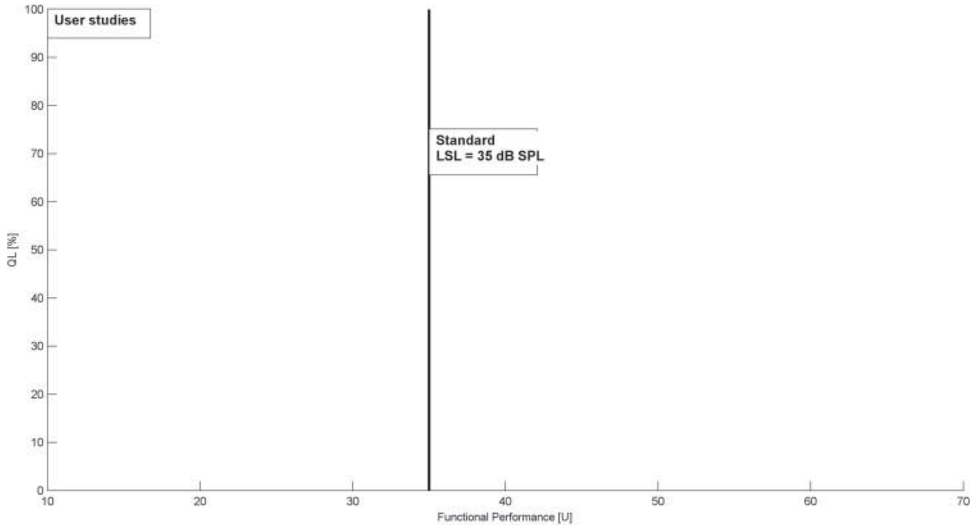

Figure 11. Audibility threshold for the 90th percentile of users.

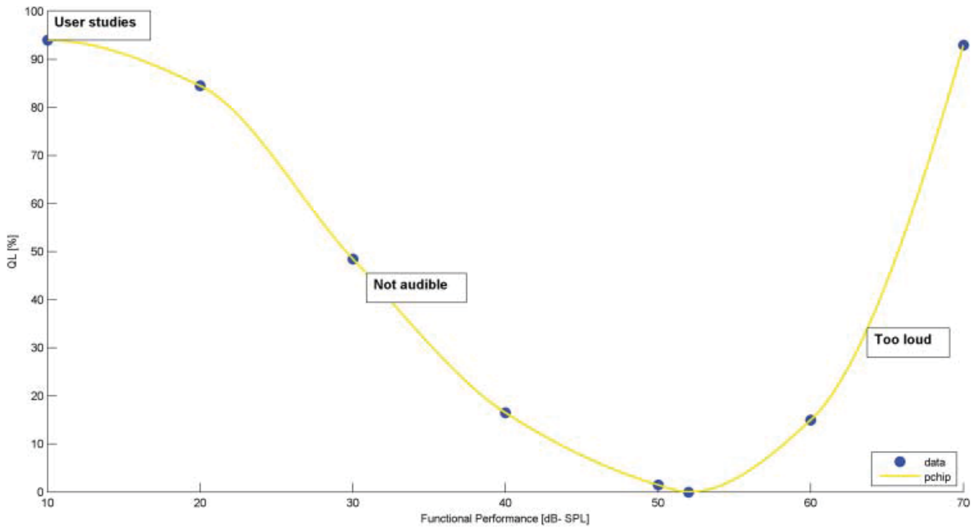

Figure 12. QLF derived by shape-preserving interpolation for Example 3 data.

development-time for future projects can be reduced. Next, a quantified interpretation will make sure the goal of the development team is aligned and reduce the risk of rework due to conflicting interpretations.

6. Discussion

In the examples, the proposed quantification tools were applied and the results illustrated by before and after visualisation of the quantified information included in the requirement. Comparing these visualisations it is evident that adding quantified information will

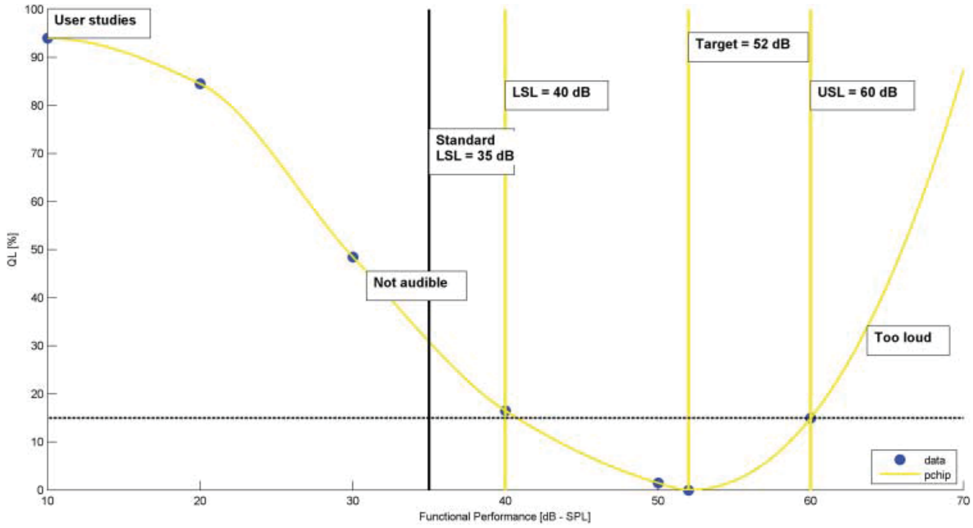

Figure 13. Example 3 requirement described using RDRS.

give a more complete picture of the impact of design decisions. In the following section the applicability and efficiency of RDRS will be discussed along with any limitations there might be.

6.1. Applicability

From the study of the case product we found that a significant number of requirements were unfit for RDRS quantification, ranging from 50% to 62.5% of the total number of requirements, depending on the type of quantification. The majority of these requirements were either procedural or categorical and many were also non-product related. Examples of non-product related requirements were requirements for test procedures, labelling, and categorisation for internal and external referencing. As RDRS is intended for the functional product requirements these findings are not considered a significant limitation of the RDRS method.

Next, we looked at the utilisation of requirements with a potential for quantification. Depending on the RDRS principle in focus, the requirements that had been quantified made up 0–69% of the potential and 0–26% of the total. The USLs and LSLs were the ones with the best utilised potential and QLFs and variation had a completely unutilised potential. First, it is worth noticing that many of the limits used in the product requirements were taken directly or somehow adapted from standards. Also, targets were mostly used for 'the smaller the better' functional performances describing an allowed variance, as seen in Example 2. These kinds of targets differ from targets set as a result of, for example, user studies, which were non-existing for the case product. This indicates that the primary purpose of the PS have been to ensure that the product complies with authority- and internal guidelines.

Overall the findings show that despite many requirements from the case product PS being unfit for quantification, those with relevance to the product design and functionality had a considerable potential for quantification, which were easy to visualise with the RDRS approach.

The case product is believed to be a good representation of many of the challenges that companies face when developing new products as a high level of uncertainty was present, due to limited user data. Furthermore, it is the impression of the authors, that the case company is very mature and competent in terms of design methodology and requirements development and management. The conclusion based on the analysis of the case company, are therefore believed to be generally applicable – and the potential benefits may be even greater for organisations operating at a lower maturity level, with less structured requirements- and development processes.

6.2. Efficiency

Ideally the design engineers should be provided with as much information as possible in a clear and accessible way without drowning them in information or restricting the solution space unnecessarily. In our own assessment this is achieved using RDRS. Often the method would require making estimates and thereby introducing uncertainty. However, the uncertainty linked to estimates is not harmful, so long as it is known. In terms of taxonomies, having no requirement information available means that, the risks can be considered 'unknown unknowns' as the design team is unaware of potential failure modes and points of interest. By analysing the customer response to changing product performance the need for upper and lower specification limits, as well as the existence of performance optima can be identified. Hereby, the 'unknown unknowns' become 'known unknowns'. Lastly, by quantifying the customer response through quantitative studies, the 'known unknowns' can be transformed into 'known knowns' meaning specific limits and targets can be assigned. As such, the RDRS encourage the design engineers to transform 'unknown unknowns' into 'known knowns' and help communicate the findings. However, RDRS is not a tool for doing the actual customer response analysis. Here, experience, qualified discussions, market research, and consumer response modelling must be used.

To summarise, the potential benefits of implementing RDRS are a reduced development-time and cost. A reduced development-time would be achieved through two effects. Firstly, the company goals would be more clearly communicated to the design engineers as quantified requirements would lead to less interpretation, misunderstandings, and ambiguity. Hereby the risk of the product not complying with internal or external requirements should be reduced, ultimately resulting in less rework. Secondly, the development process in itself would be optimised as design engineers usually, to some extent, quantify the information given in the requirement before they are able to use it. With more quantified requirements, personal and team based interpretations of the qualitatively described requirements would be controlled. Misunderstandings arisen from different interpretation and the whole process of streamlining team focus and product visions would be reduced, as seen in Example 3.

A reduced product development cost would follow from the reduced development-time, and a more determined effort resulting in fewer resources spent on sporadic hypothesis testing, last minute design changes, and an optimisation of product processes as seen in Example 1.

Another potential benefit of implementing the method would be an increased focus on identifying quality losses and sensitivity to functional variation. This may influence the way design reviews are conducted and would also create a 'pull' for answers from marketing and management in terms of what the customers and organisation require from the product. At the same time such information would make it possible for the company to direct their variation management efforts to the areas that are important to the stakeholders, hereby utilising resources more efficiently, as seen in Example 2. In other words, the tool provides a more clear direction for the design engineers and a common language for communicating between management, marketing, and the development team.

7. Conclusion

In this paper a novel approach, referred to as RDRS, for capturing and communicating product requirements has been presented. The approach was tested on a case product PS with 162 listed requirements. As the RDRS approach relies on quantified input our study included an assessment of the potential and degree of quantification of the case product requirements. It was found that product performance related requirements in particular had a large potential for quantification, whereas non-product related requirements were often found to be unfit for quantification.

Applying RDRS to a number of quantifiable requirements we found that it was possible to communicate more exhaustive and useful information than originally provided in the requirement text. Successfully producing representative and meaningful visualisations hereby served as a validation of the applicability and to some extent also the efficiency of the RDRS approach. These findings should be further validated with additional case studies from industry.

Future work will seek to validate the applicability and expected impact of implementing RDRS through industry case studies. Leading indicators to be explored will be development-time and costs, and the quality of the communication within the design team. In order to conduct industry case studies dedicated software should be developed to help facilitate RDRS. On the technical side two limitations should be addressed. Firstly, as the use of QLFs is central to RDRS an integrated solution for deriving QLFs of appropriate accuracy is an obvious addition to the presented work. Secondly, variation estimates and the optimisation of targets and limits based on these estimates along with QLFs could very well be integrated into a software solution as well.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Achieving a Perceptual Robust Design

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Abstract

The harmful effects of variation are well known in industry and many strategies for mitigating or avoiding variation exists. To address variation risks as early as possible, robust design methods can be applied in the design process. The main purpose of robust design methods is to make the performance of designs less sensitive to variation. However, the performance of a product would often be defined as the objective performance, which leaves out an important aspect – the perception of the product. The paper introduces a theoretical basis for perceptual robust design. The approach utilises the bias and limitations of the human perceptual system. Several examples are given where the utilisation of psychophysical laws are discussed in a perceptual robust design context.

Keywords: Robust design, psychophysics, perceived quality

As is widely accepted from the teaching of Taguchi (Taguchi, 1986), that variation from specifications leads to quality loss. But while variation is often easy to quantify and measure, the level of quality loss is not. This often means that the decision-making is left to gut-feel or that the quality loss is so apparent that it is undeniable. An example of the qualitative importance of conformity to specification can be seen in the Lexus ES advert from the early 90's which featured a ball-bearing rolling smoothly around the car's split-lines. This advert contained the slogan: "*So not only does the ES look like its put together well, it actually is...put together well*." This was an iconic moment for the automotive industry, when conformity and dimensional engineering was publically portrayed as an indicator of the vehicle's quality.

This led to major initiatives to improve perceived quality of vehicle build, most notably, the ATP 2 mm project, which contained a consortium of the major US automotive firms who joined together to compete with the superior Japanese and European levels of build quality. The goal was simple, in Japan the split-lines were being produced with a 2 mm gap, in Europe 3 mm but in US it was 4mm+. On completion, the project achieved its goals in variation reduction, and was measured, by conservative estimate, to have resorted in a $190 million increase in GDP.

To this day the 2 mm project stands as a reminder that quality matters and even slight variation can impact the perceived quality and consequently give rise to monetary losses. It is therefore desirable to avoid or mitigate any variation in the design. To achieve this, a number of strategies exist hereunder increasing the robustness of the design (Martin Ebro & Howard, 2016). However, there are aspects of robustness that has not yet been addressed in the robust design literature. One thing is the objective performance of a product; another is how the performance of the product is perceived by the customer. In this article a theoretical basis for how to achieve a perceptual robust product is introduced by means of psychophysics theory. The approach is called perceptual robust design and will be described in more detail in section 2.

1 Background

In the following sections a state of the art literature review on perceived quality and robust design theory is presented to support the relevance and novelty of the presented research. Lastly a brief introduction to psychophysics theory will follow to provide a basic understanding of the proposed approach.

1.1 Perceived Quality

Often the perception of products is described with a focus on product quality. This is probably the case as quality is directly or indirectly associated with the profitability of the product, which obviously is a great concern for many stakeholders. This relationship has been investigated in a number of papers looking at the link between perceived quality and KPIs more closely related to profitability, such as store traffic, or revenue growth (Babakus, Bienstock, & Van Scotter, 2004; Gotlieb, Grewal, & Brown, 1994; Rust, Inman, Jia, & Zahorik, 1999). Many definitions of quality exist and several categorisations of quality can be found in the literature. In (Stylidis, Wickman, & Söderberg, 2015) an overview of some of the most cited contributions is presented mapping how these quality categories link and overlap. Common for all the authors included in this overview is that they operate with a perceived quality category. As highlighted by (Stylidis et al., 2015) and originally proposed by Garvin (Garvin, 1984), quality can roughly be divided into two categories; the marketing oriented approach and the manufacturing oriented approach. The same goes for perceived quality, but with the manufacturing oriented approach heavily relying on physical and quantifiable measurements there is little need to concern oneself with the perception aspects. Thus, the marketing oriented approach, which to a wider extent includes subjective considerations, is where perceived quality finds the most relevance.

Looking into the components of perceived quality Forslund and Söderberg presents an overview in (Forslund, 2008). The overview has its similarities to Lancaster's theory of consumer demand, where the perception of a product is described as the result of two elements - the objective characteristics of a product and the individual reaction to these characteristics (Lancaster, 1966). Furthermore, Forslund and Söderberg's overview builds on Olson and Jacoby's differentiation between intrinsic quality cues, which are physical product characteristics, and extrinsic quality cues, which are non-physical product characteristics (Olson & Jacoby, 1972). However, they present the intrinsic quality cues as inputs for the quality appearance, which is again broken down into appearance design quality and appearance conformance quality. The appearance design quality describes the nominal design whereas the appearance conformance quality describes the conformance of products to the nominal design. This division provides a mutually exclusive and collectively exhaustive (MECE) overview, which forms a sound basis for further exploration. For instance, this overview does not provide any insight into the physical and cognitive processes underlying the forming of perception, referred to in the literature as psychophysics (see Section 1.3).

In his book Managing Brand Equity, David A. Aaker (Aaker, 1991) lists seven dimensions of perceived quality for products – Performance, features, conformance with specifications, reliability, durability, serviceability, and fit and finish. All of these dimensions agree with the intrinsic quality cues as defined by Olson and Jacoby. Furthermore, Aaker's dimensions of quality also fit well with Forslund and Söderberg's differentiation between design quality and conformance quality. Particularly, the performance, conformance with specifications, reliability, durability, and fit and finish dimensions could be said to be related to Forslund's and Söderberg's conformance quality. It is therefore argued that products which are less sensitive to variation evoke a higher perception of conformance, which is directly correlated to higher levels of perceived quality.

When dealing with perceived quality it is important to differentiate between the pre-purchase and post-purchase product valuation as described in (Amini, Falk, & Schmitt, 2014). The pre-purchase product valuation will usually be built on an immediate impression of the product in e.g. a supermarket environment. On the other hand, the post-purchase product evaluation, which becomes relevant for brand perception and repurchasing, will be based on the use of the product. Depending on the product, this use could be for an extended period of time or just a single use. In either case, the post-purchase evaluation will typically be based on far more product information, meaning that new features, functionalities, and details, including errors might be considered. This distinction is also addressed by Ophuis et. al. (Oude Ophuis & Van Trijp, 1995) where intrinsic and extrinsic quality cues are defined as with Olson and Jacoby, but with the exception that experience quality attributes and credence quality attributes are introduced. Experience quality attributes are used to describe the quality attributes that can only be ascertained through experience with the product, such as taste or convenience. Credence quality attributes are attributes that are based on credence and which cannot be experienced, which would include healthfulness or animal friendliness. Therefore, according to the Ophuis and Trijp definitions, the pre-purchase product evaluation will be based on intrinsic and extrinsic quality cues, along with credence quality attributes, whereas the post-purchase product evaluation also will be based on the experience quality attributes.

The current practice among companies for applying perceived quality methods and approaches is hard to assess. For many companies it is the impression of the authors that perceived quality is introduced implicitly as a part of voice of customers and product validation procedures. However, one industry distinguishes itself by having an open and well documented focus on perceived quality – and that is the automotive industry. Information concerning the perceived quality efforts of a number of car manufacturers is readily available online (Baker, 2013; Motor Corporation, n.d.; Tarmy, 2014). A considerable concern for car manufacturers is the visual impression, and maybe in particular, the first hand impression. Here split lines obviously play a significant role, as shown with the ATP 2 mm project mentioned earlier. But, also auditory and haptic product experiences are subject to perceived quality efforts. As a few examples, the sound of a car door closing, or the force profile experienced when activating the electric windows are areas where it is not obvious what users prefer and where significant perceived quality investigations have been conducted by companies.

A testament to the extent and history of perceived quality efforts in the automotive industry is presented in (Tarmy, 2014).

"Hop into a new $115,000 Mercedes S-Class limousine and the door will close with a satisfying, vault-like thunk. Do the same in a beat-up version from 1992 and you'll hear a sound that's eerily similar. That's because for the past several decades, Mercedes has been engineering its doors to sound reassuringly, consistently, the same."

1.2 Robust Design

As argued in the previous section there is a strong link between perceived quality and the variation found in and between products. For many companies, good quality management means controlling variation in production. However, engineering designers also plays a vital role in embedding quality into the design, through robust design methods. Robust design is used to ensure that the products performance is insensitive to variation (M. Ebro, Howard, & Rasmussen, 2012; Martin Ebro & Howard, 2016).

But what robust design methods exist? Robust design was originally introduced by Genichi Taguchi who proposed an approach known as the Taguchi method. The approach covers many aspects of product development and includes several analysis and synthesis methods, such as quality loss functions, signal-to-noise-ratios, and orthogonal arrays for use in design of experiment design studies. In short, the Taguchi method aims to improve the quality of conformance, that is, the ability of a product to meet its design requirements for the performance of the product(Taguchi, 1986). As such, the Taguchi method does not address the potential for improving the robustness of the design in the perceptual domain.

Since the introduction of the Taguchi method the field of robust design has evolved and many new methods and perspectives have been introduced. In (Suh, 1990) Suh introduced his work on axiomatic design, which has since become a widely used approach in robust design. Several methods coming from the more general design theory has also found its use in robust design, such as design clarity, and basic tolerance chain analysis (Pahl & Beitz, 1996). More recent contributions have introduced new optimisation tools and approaches (Cheng, Xiao, Zhang, Gu, & Cai, 2014; Wang, Xiao, & Gao, 2015; Yildiz, 2013).

Furthermore, to support robust design methods and to visualise the effects, loss functions have been used to optimise between multiple quality indicators (Hazrati-Marangaloo & Shahriari, 2016; Soh, Kim, & Yum, 2016). This way the sensitivity information can be fed into the product development process, for instance, as part of the requirements using a method such as the Robust Design Requirements Specification (Pedersen, Christensen, & Howard, 2016).

However, none of the mentioned robust design methods address the robust design opportunities found in the perceptual process, which is why the approach of perceptual robust design is proposed in this article.

1.3 Psychophysics

In his book “Psychology” Harvard Professor Daniel Schacter defined perception as “the organization, identification, and interpretation of sensory information in order to represent and understand the environment” (Schacter, Gilbert, & Wegner, 2011). From the view of objective reality the process of perception is where the individual interpret the objective world and hereby creates a subjective understanding of it. The field of psychophysics studies this relationship between physical stimuli and human sensation, perception, and cognition and include elements from psychology, neuroscience, and physics. Many of the original psychophysics theories were proposed by Gustav Theodor Fechner in 1860, meaning the field have existed for more than 150 years. However, to the best knowledge of the authors, the robustness of product perception has not yet been investigated in a psychophysics context.

In psychophysics the process of turning information, in the form of physical stimuli, into a e.g. percept of the external environment is studied (Gescheider, 2013). To gather information about the external environment humans possess a sensory system. The information collected though the receptors, of the sensory system, is referred to as sensory information. This information is processed by the central nervous system to produce a percept of the external environment on which actions and decisions can be made to best serve an interest (Ernst & Bülthoff, 2004; Kolb & Whishaw, 2015). Assuming there is no bias in the processing of sensory information, accurate information will always be the best basis for taking the right actions. However, no sensory modality is perfect. Each of our senses can only capture information given by the physical stimulus that provokes a response from that specific type of sensory receptors. Depending on the situation this information is used to construct the most valuable percept given our limited processing power. For instance, in a well-lit room one would typically use the visual modality as the primary source of information when deciding the additional content in the room. However, if the light is turned off and the room turns pitch black no useful information can be obtained from the visual modality and other modalities, such as listening or touch, will have to be used instead. This weighting of sensory information is obviously very important in order to exclude biased or compromised information and combine information coming from several sensory modalities in the most efficient manner.

From an evolutionary point of view the sensory system is the result of the best adaption for survival and reproduction in a given environment. Therefore, the human sensory system is not adapted to accurately perceive many of the elements encountered in a modern society. For the vast majority of human existence and the existence of human ancestors the recognition of eatable sources of nutrition and staying alive, e.g. avoiding superior predators and rivals, has been the main priority. In modern civilized societies these requirements are no longer as crucial. Most threats that still exist have changed and the ability to recognize eatable sources of nutrition is hardly necessary anymore. We are, however, faced with many new environmental stimuli, for instance coming from the products we surround ourselves with. In this article the focus is on the difficulties and opportunities that comes from assessing products using a sensory system that has evolved from circumstances that is not necessarily aligned with the information gathering and processing best suited for assessing these products. And in particular how this knowledge can help form new mitigation strategies for coping with variation of different kinds in product design.

2 Perceptual Robust Design

As described in section 1.2 robust design methodology covers a wide range of methods and approaches. Common for all is that they address the performance of products. However, most would agree that the perception of a products performance is what matters. Addressing only the performance with robust design efforts is therefore either assuming that the difference between the performance and perception is negligible or simply that there is no useful purpose of addressing the perception side. However, both assumptions would be wrong. The human perceptual system has been adapted to changing environments for millions of years in a way that best supports our ability to survive and reproduce. The outcome is a biased system with many limitations. In perceptual robust design this bias and these limitations are exploited to create product designs for which the product percept is less sensitive to variation in product performance and appearance.

Perceptual robustness can sometimes be a trade-off and should not be confused with the related topic of customer preference. To take a simple example, consider paint colour. In terms of customer preference, the customer may prefer the red paint rather than the blue paint. However, in terms of perceptual robustness, the customer may be able to perceive more variation in shades of red (less robust) than of shades of blue (more robust); meaning if they were to fade at the same rate, the customer would perceive greater fading of the red paint. In some instances customer preference is the more important, in others, the perceptual robustness is more important depending on the customer satisfaction profiles for each of the design options. In Figure 1, fictitious preference data for a red and blue design option is shown. At 100% colour saturation red is preferred by customers, with red scoring 100 and blue only scoring 90 on an arbitrary rating scale where 100 is the best. However, the saturation of colour might vary for products coming out of production and over time. For one reason or another, saturation might decrease to 70% for a considerable amount of products. As the fade of the blue colour is less noticeable and therefore appears less faded, blue is now the preferred colour.

Therefore, knowing about the user preferences and the expected variation, designers will be able to optimise the design to maximise the user experience.

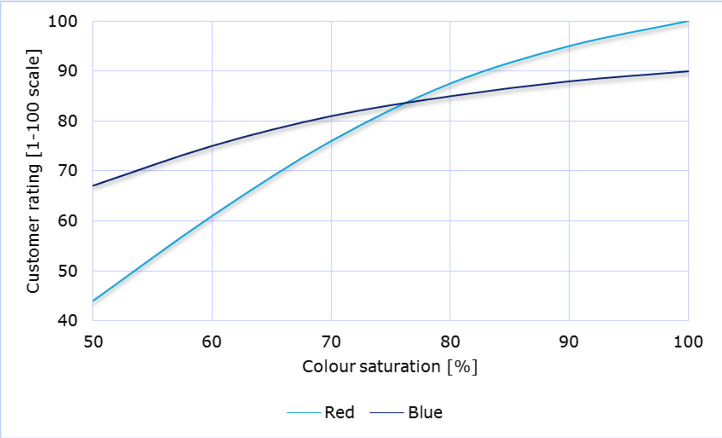

Figure 1. User preference curves for red and blue. At 100% saturation customers prefer red, but as saturation fade blue becomes more preferred as the fade is less perceivable.

In Figure 1, a customer rating is linked directly to the colour saturation of the product. In reality such data will be heavily influenced by a vast number of parameters other than the product colour, such as other design features, intended use, target customer group, etc. It is therefore hard to generalise about user preference. It is, however, possible to generalise about the capabilities of the human perceptual system. To do so psychophysics provides useful theory by describing the link between physical stimuli and sensory, perceptual, or cognitive measures. In this article, however, the focus will be only on perceptual measures. Mathematically the psychophysical descriptions can be regarded as transfer functions where the sensitivity of the perceptual measure is given by the derivative of the transfer function. This interpretation will be used in the following section to discuss psychophysics theory in a perceptual robust design context.

3 Utilising Psychophysics in Perceptual Robust Design

To substantiate the approach of perceptual robust design some of the existing psychophysics theory will now be presented and examined in a perceptual robust design context. The psychophysics theory that is presented was chosen based on its relevance to perceptual robust design and its overall applicability. A few general laws of psychophysics have been recognized as applicable in many cases across sensory modalities. In his book "Sensory Neuroscience" Zwislocki proposes four such laws of which two is highly relevant in a robustness context and will be examined in the following. Furthermore, additional laws of a more specific nature and judged to be of relevance to perceptual robust design, will also be reviewed along with other experimental findings from the literature.

3.1 Stevens' Power Law

The first general law of psychophysics that will be covered it Stevens' power law. According to Steven's power law the relationship between stimulus intensities and sensation magnitudes is described by the following power function

$$(1)\quad \psi(I) = kI^{a}$$

Where ψ is the subjective sensation magnitude, I the magnitude of the physical stimulus, a is a power exponent depending on the stimulus type, and k is a dimensional constant that depends on the units used. It is here important to note that the percept is limited to the perceived magnitude of the sensation (Zwislocki, 2009). In table 1 the exponents for 22 different sensations found by Stevens is listed.

Table 1. In second column exponents for 22 different stimuli found by Stevens is listed (Stevens, 1957)**. The stimulus type is listed in the first column and stimulus conditions are briefly described in the third column.**

Stimulus	Exponent (a)	Stimulus condition
Brightness	1	Point source briefly flashed
Brightness	0.5	Point source
Cold	1	Metal contact on arm
Duration	1.1	White noise stimuli
Electric shock	3.5	Current through fingers
Heaviness	1.45	Lifted weights
Lightness	1.2	Reflectance of grey papers
Loudness	0.67	Sound pressure of 3000 Hz tone
Muscle force	1.7	Static contraction
Redness (saturation)	1.7	Red-grey mixture
Tactual hardness	0.8	Squeezing rubber
Tactual roughness	1.5	Rubbing emery cloths
Taste	1.4	Salt
Taste	0.8	Saccharin
Thermal pain	1	Radiant heat on skin
Vibration	0.95	Amplitude of 60 Hz on finger
Vibration	0.6	Amplitude of 250 Hz on finger
Visual area	0.7	Projected square
Visual length	1	Projected line
Warmth	1.6	Metal contact on arm
Warmth	1.3	Irradiation of skin, small area
Warmth	0.7	Irradiation of skin, large area

Similar exponents could be found for almost any well-defined sensation. However, test conditions are of great importance and should always be carefully chosen and analysed.

Stevens' power law entails that for $0 < a < 1$, the sensation magnitude is described by a concave upward and increasing curve, for $a = 1$, the sensation magnitude is linearly proportional to the stimulus, and for $a > 1$, the sensation magnitude is described by a concave downward and decreasing curve.

Steven's Power Law in a Perceptual Robust Design Context

Now, what does Stevens' power law tell us about how products are perceived by customers? Well, as given by equation (1), for values of $a > 1$ the sensitivity of the magnitude sensation increase when I increase and for $0 < a < 1$ the sensitivity of the magnitude sensation increase when I decrease.

The relationship between the power function and the sensitivity of the output becomes clear when differentiating the power function, leaving an expression for the sensitivity of the subjective sensation magnitude.

$$(2) \quad \frac{d\psi}{dI} = akI^{a-1}$$

For $0 < a < 1$, as $I \to \infty, \frac{d\psi}{dI} \to 0$ and as $I \to 0, \frac{d\psi}{dI} \to \infty$

Likewise, for $a > 1$, as $I \to \infty, \frac{d\psi}{dI} \to \infty$ and for $I \to 0, \frac{d\psi}{dI} \to 0$.

The data reported in Table 1 is interesting in itself. For example, product developers may choose to hide changes in vibration level by maximizing the amplitude within the acceptable interval, or perhaps choose a more intense red colour indicator so that users can better notice the change in colour. However, perhaps even more interesting to note, than the data, is the nature of the sensation magnitude. The very fact that for some stimuli, the value of the exponent a is not equal to one, gives the opportunity to find more perceptual robust or sensitive regions. This can be utilized to either mask the user's perception of variation or to heighten their awareness of change.

For instance, assuming there is a negatively correlated link between the amount of variation in I and the perceived quality of the product. Then follows from the above deductions that for stimuli where $0 < a < 1$ the most robust design in terms of perceived quality is achieved when I takes a high value and vice versa for $a > 1$. Furthermore, such data can be used to compare the robustness of different design options. For instance, values of a might be found for colour saturation for greenness and blueness in addition to the values listed in Table 1 for redness. Say the exponents arrive at 1.8 for greenness and 1.6 for blueness. If there is a variation in the colouring of our product these values tell us that customers perception of saturation will be significantly more sensitive to green than to blue. Therefore, it is reasonable to believe that variation in saturation is less likely to be noticed or at least will be recognized as of less magnitude for a blue product than for a green product. Similar examples could be found for curvatures, gaps, line lengths, force profiles, etc. In cases where these perceived differences or changes in a product are important, companies could conduct their own studies to test perception magnitude of a particular parameter.

3.2 Weber's Law

Weber's law states that for sensory experiences there is a constant ratio between an initial stimulus and the difference from that stimulus required for the change to be perceivable. This change is typically called the just noticeable difference (JND) also called the difference threshold. The law is captured by the following expression:

$$(2) \quad \frac{\Delta I}{I} = k$$

Where ΔI is the JND, I the reference stimulus, and k is a constant denoting the ratio between the reference stimulus and the difference threshold (Zwislocki, 2009). $\frac{\Delta I}{I}$ is here what is called the Weber fraction. In Table 2 examples of Weber fractions for five different sensory stimuli are shown.

Table 2. In the second column the Weber fraction for five different stimuli is listed. The stimulus type is listed in the first column (Teghtsoonian, 1971)**.**

Stimulus	**Weber fraction**
Electric shock	0.01
Lifted weight	0.02
Sound intensity	0.04
Light intensity	0.08
Taste (salty)	0.08

As given by equation 2 the Weber fraction can be interpreted as the percentage change from the original stimulus required for the change to be perceivable.

A number of limitations apply to Weber's law. Firstly, it mainly applies for first-order structures such as weight, length, pitch, or brightness. Secondly, inconsistencies known as "near miss" incidences for

Weber’s law have been recorded in the visual and auditory domain for relatively weak or strong signals (Kundu & Pal, 1986)(McGill & Goldberg, 1968).

Weber’s Law in a Perceptual Robust Design Context

From a robustness point of view a large value of ΔI is desirable as it would mean large variation would have to be present before users would notice a difference. As a general rule following Weber’s law, the stronger the stimulus the larger the JND, and thus strong signals are preferred from a robustness point of view. Rewriting equation 2, the following expression is found:

$$(3)\quad \frac{\Delta I}{I} = k \;\Rightarrow\; \Delta I = kI$$

From equation 3 it is evident that the JND, ΔI, is the product of I and k. Thus, by studying values of k for different design alternatives the most robust solution can be found. Furthermore, a range of I, relevant for the design, can typically be found. Depending on k the benefit of maximizing I can be evaluated.

However, if we compare Weber’s Law and Stevens’ Power Law we notice that they are somewhat contradictory. While Weber’s Law suggests that the greater the initial voltage of an electric shock, the less the subject is able to perceive any change in voltage. However, Stevens’ Power Law suggests that the sensitivity of sensation magnitude increases at higher voltages. This could be explained by the different scales used. Where Weber’s Law is concerned with the just noticeable difference Stevens’ Power Law looks at the sensation magnitude. Intuitively these two measures would be negatively correlated – when the sensation magnitude increases the JND decreases. In addition to the different scales it is also likely that the range of data used for deriving these laws are incomparable. As mentioned earlier Weber’s Law have shown inconsistencies for relatively weak or strong signals.

3.3 Sensitivity of Sensory Modalities

This section concerns research related to the three sensory modalities, visual, haptic, and auditory that mainly influences a user’s perception of a physical product. Each law and study is reflected on with respect to how variation in the sensory information is perceived by t the subject (the user) and therefore what can be learned from a perceptual robustness point of view.

3.3.1 Visual

The human visual system (HVS) is a very complex and not fully understood system. However, laws and models exist to describe some of the mechanisms of the HVS. In the following, some of these laws and models are presented and as earlier, interpreted in a robustness context.

3.3.1.1 Summation in the detectability of light

Bloch's law states that the detectability of light can be described as a function of time and light intensity as given by equation 4 (Bloch, 1885).

$$(4) \quad T * I = C_{Bloch}$$

Where T is time, I is intensity, and C_{Bloch} is a constant threshold value. This means that the eye is capable of summarizing light intensities over a period of time, also known as temporal summation. For rod photoreceptors (twilight vision) this period is approximately 100 ms and for cone photoreceptors (daylight vision) it is approximately 10 to 50 ms.

In addition to temporal summation, the visual system is also able to do spatial summation for detecting light. By spatial summation is meant the ability to add up light intensities from an entire area. How it adds up depends on the stimulus area. For small areas where $A < 10\ MOA$ Ricco's law applies and for larger areas where $10\ MOA < A < 24\ MOA$, Piper's law applies. MOA is an angular unit that stands for minutes of arc where $1\ MOA = \left(\frac{1}{60}\right)°$.

Much like Bloch's law, Ricco's law states that the detectability of light can be described as a function of the retinal area stimulated by a light stimulus and light intensity, as given by equation 5 for $A < 10\ MOA$ (Matin, 1975; Ricco, 1877)

$$(5) \quad A * I = C_{Ricco}$$

Where A is retinal area, I is light intensity, and C_{Ricco} is a constant threshold value. In short, Ricco's law means that the detectability of a light stimulus is unchanged if we double the intensity and half the size of the area.

If the retinal area stimulated by a light stimulus $10\ MOA < A < 24\ MOA$ the effectiveness of the summation starts to decrease. This is captured by Piper's law given by equation 6 (Colman, 2009; HOWARTH & LOWE, 1966)

$$(6) \quad \sqrt{A} * I = C_{Piper}$$

The actual detectability threshold for light, that is, the number of photons necessary to cause a perceivable stimulus, has been the subject of investigation for many years. A recent study (Tinsley et al., 2016) has shown that a single photon is detectable by the human eye and conscious mind. However, factors such as background lighting, biological differences, etc. play important roles. The point being that in order to derive a detectability threshold for light, experimental data for the intended observer environment and situation should be obtained.

Perceptual Robust Design Context

There are many applications of light-based transmitters and sensors in products. In most applications the light emitted should not be detectable by the user. In some instances this is solved by moving the frequency beyond the visible region, but in some cases it might be beneficial instead to reduce the intensity and increase the length of the pulse or increase the intensity and reduce the area.

When considering Bloch's law in a robust design context two different design intensions should be considered. Firstly, that a light stimulus is intended to be perceived by the user. And secondly, that a light stimulus is not intended to be perceived by the user. In the first case time and intensity should be maximized and in the latter case time and intensity should be minimized to create the most robust design.

Just as for Bloch's law two different design intensions should here be considered. Firstly, that a light stimulus is intended to be perceived by the user. And secondly, that a light stimulus is not intended to be perceived by the user. In the first case area and intensity should be maximized and in the latter case area and intensity should be minimized to create the most robust design.

Taking the square root of A slightly changes the situation as the weighting factor is no longer one to one between the two variables. A change in A will now have a smaller impact on the detectability of the light stimulus than a similar change in I, meaning I is the most sensitive variable.

3.3.1.2 Visual Detectability of Regularity

In many aspects of life the detection of regularity, and in particular symmetry, is important. For instance, facial symmetry is a leading factor when choosing partner (Fink, Neave, Manning, & Grammer, 2006; Grammer & Thornhill, 1994). This is the result of an evolutionary process where the potential for surviving and reproducing has been correlated with face symmetry.

Many measures of the detectability of regularity exist. The one presented in the following is proposed by Van Der Helm in (van der Helm, 2010) and is based on the holographic approach to visual regularity. It has been chosen here as it is more generally applicable and yet performs well compared to more specialized approaches. The approach states that detectability and strength of a regularity, as found in symmetric patterns, is described by the following expression.

$$(7) \quad p = g * W = g * \frac{1}{2+N/R}$$

Where p is a measure of the strength of the regularity percept, g is a proportionality constant, which depends on the visual system and will have to be determined experimentally, and W is a weight-of-evidence metric. In the latter part, N is the number of noise elements and R is the number of structural relationships between elements forming symmetry pairs. An example is given in Figure 2, where noise elements are denoted N and symmetry pairs are denoted R_1, R_2 and R_3.

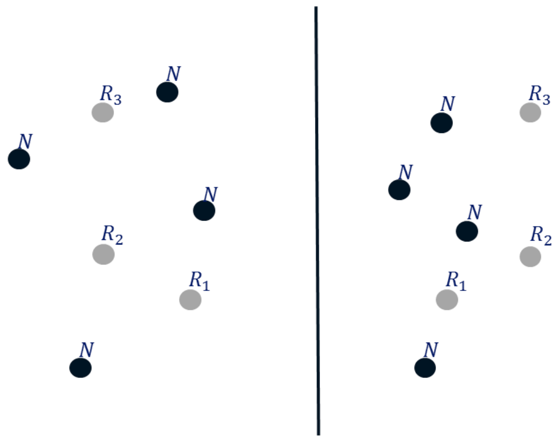

Figure 2. A pattern with three grey symmetry pairs denoted R_1, R_2 and R_3 and noise elements denoted N.

Perceptual Robust Design Context

Just as with facial symmetry, symmetry can be a measure of quality when it comes to products. Based on experience and detected symmetry patterns a notion of the intended design is created, which is used as reference for our quality evaluation.

As given by equation 7, the strength of the regularity percept is controlled by the ratio between noise elements and the number of structural relationships. Meaning that, if $N/R \rightarrow 0$, then $p \rightarrow \frac{g}{2}$, which is the maximum value p can assume. Assuming that large changes in the strength of the regularity percept, p, is closely and positively correlated with the JND, a more robust design could be achieved by decreasing the impact of the individual structural relationships, R. Meaning we want to minimise

$\left|\frac{N}{R} - \frac{N}{R+\Delta R}\right|$. This is achieved for $N \to 0$ and $R \to \infty$. Thus, by reducing the number of noise factors and increasing the number of structural relationships a more robust regularity percept is achieved.

3.3.1.3 Just Noticeable Difference for Colour

The perception of colour is significantly influenced by the size of the coloured object (Fairchild, 2005). As a consequence the JND for robust differentiation between colours is significantly dependent on the size of the coloured object. In the following a model for describing how JND of colours depends on size, is presented (Stone, Szafir, & Setlur, n.d.). The model is based on the CIELAB colour scale meaning a given colour is described by three entities – the lightness L, and a and b, which are colour-opponent dimensions (Hurvich & Jameson, 1957).

$$(8) \quad ND(p, s) = p(A + \frac{B}{s})$$

In the above equation ND is the JND vector containing values for L, a, and b. ND is a function of p, which is the percentage of test subjects that perceived a difference and s, which is the size of the object measured in degrees of arc. A and B are constant vectors determined experimentally and presented in (Stone et al., n.d.). The values are given from Table 3.

Table 3. CIELAB colour scale values for vector A and B, where L describes the lightness and a and b describes colour-opponent dimensions.

Axis	A	B
L	10.16	1.50
a	10.68	3.08
b	10.70	5.74

Perceptual Robust Design Context

From equation (8) it is given that the size of the object is negatively correlated with the JND. This means that if the size of the product is increased it is easier to tell if there is a difference in the colour.

A simple application of this theory is when deciding on painted or anodized surfaces. Coatings which have large variation in the intensity or thickness may still appear high quality, so long as the area of coverage is small enough. It may be in some instances, the surface quality of an object is of poor quality meaning that an even coverage of a coating is unlikely. If the object is large the irregularity will be more easily noticed by the customer. To minimise this effect, large surfaces of the object could be broken down into smaller surfaces on different levels (easily achieved if casting or moulding) or a pattern or multi-colour/shade pan job could be selected in order to minimise the area of any one colour.

3.3.1.4 Visual Selective Attention

Recent studies suggest that visual selective attention is best described by a hybrid model combining two opposing views – the early selection view and the late selection view. The early selection view argues that by focusing the visual attention, distracting visual information can be prevented from being perceived (Broadbent, 1966; Treisman & Geffen, 1967; Yantis & Johnston, 1990). The late selection view on the other hand argues that distracting visual information can only be excluded in the post perceptual processing (Deutch & Deutch, 1963; Duncan, 1980; Tipper, 1985). According to the hybrid models suggested by Lavie, among others, the perceptual load of the visual stimuli will determine if information is excluded in the pre- or post-perceptual processing (Lavie, 1995, 2001; Lavie & Tsal, 1994). When the perceptual load is high, meaning that much information must be processed, there is little capacity for processing irrelevant information, and thus early selection occurs. If the perceptual load is low, then there is a surplus of processing capacity which automatically will be used on irrelevant information to be excluded post perceptual, meaning the late selection will occur (Lavie & De Fockert, 2003). In a recent contribution Stolte et. al. showed that high perceptual loads increased the contrast threshold in a colour conjunction experiment (Stolte, Bahrami, & Lavie, 2014), which indicates that the threshold for recognising variation increases.

Perceptual Robust Design Context

The perception of elements considered irrelevant to the task at hand, will be highly dependent on the perceptual load of the task. With limited processing capacity it is therefore reasonable to assume that the sensitivity of the perception of irrelevant elements will decrease as the perceptual load of the task increases. The implications are that the aesthetic quality requirements of peripheral features need not be as high when the user is undertaking task with high perceptual load in comparison to when the user is in a more idle state. This could certainly play a role in the effective tolerance allocation, where tolerances should be allocated with respect to the perceptual loading.

3.3.2 Haptic

The haptic sensory system provides kinaesthetic and tactile sensing. The kinaesthetic system provides information about movement, relative positioning of body parts, and forces acting on the body. The tactile system provides information of roughness, lateral skin stretch, relative tangential movement, and vibrations. From these sensations texture, shape, compliance, and temperature can be deducted into a percept. (Mihelj & Podobnik, 2012) (Fox, 2002). In the following a selection of haptic JNDs and detection thresholds are described and discussed in a robust design context. The selection was based on available literature and relevance to robust design.

3.3.2.1 JND for Slowly Varying Forces

For slowly varying forces the JND for human force sensing is around 7% regardless of test conditions (Tan, Srinivasan, Eberman, & Cheng, 1994) corresponding to a Weber fraction of 0.07.

Perceptual Robust Design Context

JND information for slowly varying forces is an extremely useful quality guideline for a huge number of applications. This could set the robustness requirements for the allowable variability from one product to the next, from one use to the next, or even throughout a single use. It could also be used to specify the dimensional tolerances of buttons and switches in an interface, to ensure that one button does not feel stiffer than another.

3.3.2.2 Detection Threshold for Vibrations

For vibrotactile stimulation the detection threshold is roughly 28 dB below 30 Hz and decreases at a rate of roughly -12dB/oct from 30 to 300 Hz, where an octave is a doubling of the frequency. For frequencies above 300 Hz the detection threshold rises again up to 1000 Hz which is the upper limit of what the human somatosensory system can perceive (Tan et al., 1994)

Perceptual Robust Design Context

The above information is especially useful when setting tolerance limits. In some cases the designer might intent for the vibrations to be detectable and it will be used as a lower tolerance limit. In other cases the vibrations are not intended to be detectable and it will be an upper tolerance limit. As the detection threshold is at its lowest around 300 Hz it can be assumed that the sensitivity to changes is also at its highest around 300 Hz. Therefore, a more robust design in terms of the vibration sensation would be achieved for very low or high frequencies.

3.3.2.3 Pressure

JND for pressure depends heavily on gender and location on the body, ranging from roughly $5\ mg/mm^2$ on a woman's face to $355\ mg/mm^2$ on a man's big toe (Corso, 1967; Rutherford, 1987; Weinger, Wiklund, & Gardner-Bonneau, 2010; Woodson & Conover, 1964)

The JND for pressure applied to forearm decreases as the contact area increase. Applying quantitative estimates this decrease has been recorded with a factor of four as the area increased with a factor of 16 (Tan et al., 1994).

The detection threshold for pressure also depends on gender and location on the body. However, to successfully activate the pressure sensors a force greater than 0.06 to 0.2 N per cm^2 must be applied (Hale & Stanney, 2004).

Perceptual Robust Design Context

Firstly, from above data it is clear that the sensitivity to pressure varies by a factor of 71 depending on location and gender. While gender is not something that can be changed in the design, the location at which a product is in contact with the body can. Thus, from a robustness point of view contact with the big toe or other less sensitive regions are preferable. Of course, where the product will need to exert pressure in order to provide feedback to the users the more sensitive regions may be more suitable.

Secondly, for explaining the correlation between JND and contact area a theory is that the sensory system mostly recognises pressure gradients and thus, the perimeter of the area is what helps detect differences (Tan et al., 1994). Therefore, sensitivity increases with perimeter of contact area and the most robust design will be achieved for small contact areas. However, the pressure is given by:

$$P = \frac{F}{A}$$

where F is the force and A is the area. Meaning that by reducing A, the pressure is increased. Typically, variation in pressure would arise from variation in F, meaning that by reducing A the variation of P is also increased. To determine the most robust pressure area one must therefore consider both the effect on JND and pressure standard deviation.

With basis in the above data the change in JND as a function of area can be described in mathematical terms as:

$$\Delta JND = \left(\frac{A - A_0}{A_0}\right) * 0.25 * JND_0$$

The optimal area can now be found by looking at the estimated variation in force, here given by the standard deviation of the force applied, σ_{force}.

Assuming the area is constant, the standard deviation of the pressure is thus:

$$\sigma_{pressure} = \frac{\sigma_{force}}{A}$$

3.3.2.4 Haptic Detection Threshold for Rigidity

Measured as N/cm the average threshold point for perceived rigidity based solely on haptic information was recorded at $242\ N/cm$ in a study by (Tan et al., 1994). However, the detection of rigidity is of a more complex nature than e.g. basic touch, and as such a higher level of subjectivity will be involved. Thus, the threshold ranged from $153\ N/cm$ to $415\ N/cm$ between test subjects. For all test subjects the cantilevered beam used in the experiment was visibly bent at the point of detection threshold. Meaning it is likely that the threshold point for rigidity would decrease if the visual modality was included.

Perceptual Robust Design Context

This is an area where customer preference, anthropometrics and perceptual robustness may heavily overlap. To begin with, it is important to understand the desirability of "rigidness". It is the case that in many products the more ridged and study the better. This not only impact the stiffness and dimensions of the materials being used but also the fit and the amount of play within component joints. Assuming the higher the perceived rigidity the better, the product designers can alter the dimensions to both control the amount of force that the user will be able to exert (small gripping surfaces) and the amount of deflection that will occur. The product can therefore be designed to limits of perceptual rigidity.

3.3.3 Auditory

Hearing is made possible by the auditory system. The physiology of the auditory system will not be described here, but in short two main stimuli parameters control the perception of the sound stimuli – frequency and amplitude. To describe the power of a sound signal the sound intensity level (SIL) is used. SIL is calculated from equation 9.

$$(9)\quad SIL = 10\log_{10}\left(\frac{I}{I_0}\right)\ dB$$

Where I is the sound intensity given as W/m^2 and I_0 is a reference value typically set as the hearing threshold at $10^{-12}W/m^2$ (Meyer & Neumann, 1972).

3.3.3.1 Detection Threshold

In the following detection thresholds and JNDs for the frequencies and amplitudes are presented and discussed in a robust design context.

For frequency the upper and lower detection threshold is 20 Hz and 20kHz, respectively.

Given in sound intensity the detection threshold for amplitude is, as given above, $10^{-12}W/m^2$. Relating sound intensity to the subjective perception of sound loudness the unit of phon is used, where 0 phon equals the hearing threshold and 100 phons is the threshold of pain. As seen from the equal-loudness contour plot in Figure 3 the perception of loudness very much depend on the frequency of the signal.

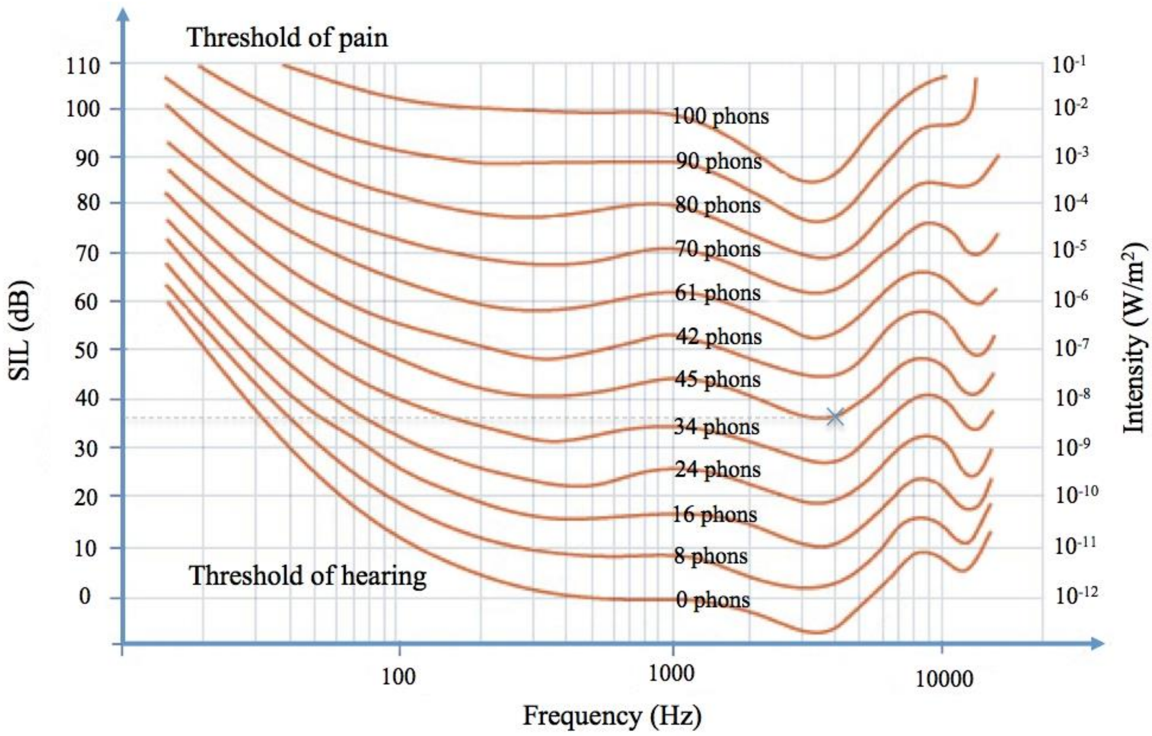

Figure 3. Equal loudness contour plot. Each contour line shows equal loudness with varying frequency and SIL. (Fletcher, 1991)**.**

3.3.3.2 JND

Studies by (Harris, 1952; Jesteadt, Wier, & Green, 1977) have investigated the JND for frequency and loudness. The data is shown in Figure 4.

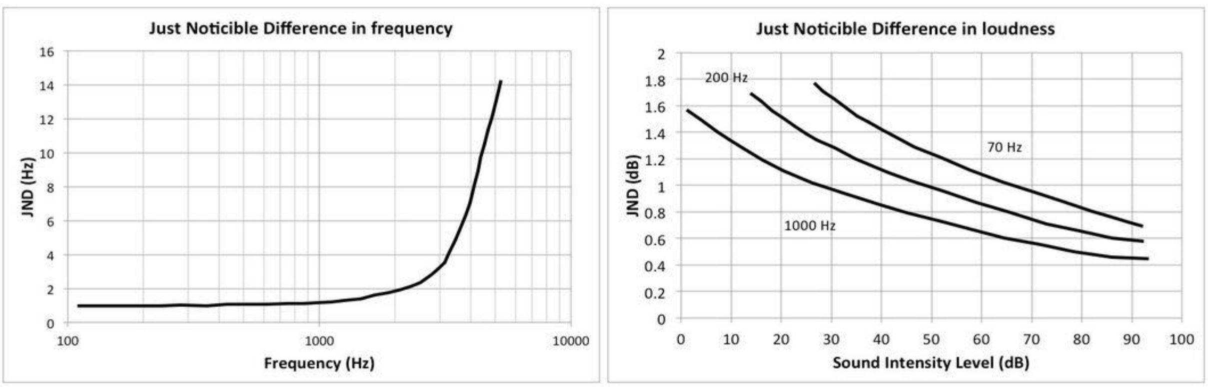

Figure 4: To the left, the just noticeable difference in sounds is shown as a function of frequency. To the right, the just noticeable difference is shown as a function of sound intensity level and discrete levels of frequency (Harris, 1952; Jesteadt et al., 1977)

For frequency it appears from Figure 4 that the JND for pure tones is close to constant up to 1000 Hz after which it rapidly increases. Considering different frequencies of pure tones the JND for loudness decreases for levels up to approximately 100 dB SPL (Plack, 2005). Furthermore, as seen in Figure 4 there seems to be a negative correlation between frequency and JND in the range between 70 Hz and 1000 Hz. Similar results have been found for white noise signals, but for sound intensity levels above a certain level the JND for pure tones tend to continue to decrease whereas it stays constant for white noise. Different results have been found for the level at which JND becomes constant for white noise. Some suggest in the 80 dB region (Foley & Matlin, 2016) whereas others suggest white noise JND finds a constant value already in the 40 dB region (Buser & Imbert, 1992).

Perceptual Robust Design Context

To ensure as robust a design as possible it is desirable to increase the JND as much as possible. However, the JND for frequencies is more robust for high frequencies, whereas the JND for loudness is the most robust for low frequencies. Knowing the variation to expect it is easy to establish whether a change in frequency or loudness will be noticed the first and thus which one to prioritize in the robust design efforts.

4 Discussion

In this section the applicability of the above presented research will be discussed along with some of the limitations that apply to this approach. Lastly, future work will be discussed.

4.1 Applicability of Perceptual Robust Design

The use of the presented theory in a robust design context can be approached at two levels - as general design guidelines, and as a design optimization tool.

As argued earlier both Stevens' Power Law and Weber's Law can be used to deduct general design guidelines using the exponent or fraction, respectively, to explain tendencies of perception arising from the design. Such guidelines can be very useful to ensure some level of robustness without restricting the design significantly. For instance, in "everything else being equal" situations it can be used to choose the more robust option, being a choice of colour, geometry or something else. In usability or safety situations, where user preference is of less importance, it could also provide valuable inputs by identifying the design that creates the most reliable and robust percept.

If accurate data is available it could even be used for optimizing the design ensuring the optimal trade-off between user preference and robustness for the best overall market response. However, it is likely to be a costly exercise deriving this data, and would therefore mostly be relevant for companies and products with large revenues.

In this article existing psychophysics data have been presented. Design situations are conveivable where the presented data could provide a good design guideline, but more generally, having the basic understanding of these psychophysics laws will enable the designer to hypothesise how variation will be perceived by the users. However, often product/use specific data will be required, especially if interactions between design parameters or with external parameters are influential.

4.2 Proposed Method for Applying Perceptual Robust Design

Perceptual robustness considerations could be applied in an ad-hoc and opportunistic manner by product designers. However, if investigated for experiments and data acquisition is required; a more systematic process could be beneficial. The Key Characteristics method (Thornton, 2004) could be used to delimit the extent of variation related investigations, to the most influential parts of the design and could therefore provide a suitable framework to pin a perceptual robustness process on. As part of the method, characteristics are flowed-down from what matters to the customer, to what is likely to vary in the design. Characteristics that both matter to the user and have a high risk of variation are termed as key characteristics. The following process steps combine the requirements for data acquisition and use for achieving perceptual robustness and the Key Characteristics approach:

Steps:

1) Identify top level KCs (What matters to the user)
2) Flow-down KCs to design features and functions (What is likely to vary in the design)
3) Identify the sensory domains pertaining to each design feature/function (Visual, auditory, haptic, etc.)
4) Identify if any known laws/theories/data explains perception of design features/functions
5) Obtain own data on perception of design features/functions (e.g. DoE)
6) Analyse data and identify options for improving perceptual robustness
7) Analyse to what extent perceptual robustness contradicts or align with user preferences
8) Update design based on robustness and preference data

The above steps are only intended to inspire further research on the topic. The steps are not validated in any form and should not be considered a part of the perceptual robust design approach, which at this point only encompasses the notion of utilizing psychophysical models to design more robust products.

4.3 Limitations

A number of limitations apply when using psychophysics theory to achieve more perceptual robustness from a product. Most importantly the perceptual processes of the mind are very complex and influenced by many parameters. Some signals mask each other, some distort each other, and some amplify each other.

Multimodal perception is a step towards the “real-life” perception of products. Rarely will a person be in a situation where only information from one sensory modality is used to create the percept. Rather a wide variety of information from all modalities, weighted differently, is how we perceive the environment the vast majority of the time. When combining modalities the potential for product development relevant studies is huge as the number of potential interactions between sensory modalities is vast and is easily related to customer satisfaction. An example of a type of multimodal (crossmodal) study is affective ventriloquism. Affective ventriloquism is the phenomenon of affecting the experience obtained through one or more sensory modalities through another sensory modality (Spence & Gallace, 2011). For instance, by colouring the bottle of sparkling water light yellow and thereby introducing a citrus association, which is a gustatory sensation. Temporal simultaneity is another example, which has to do with the ability to distinguish or align sensory inputs in the time domain. The perception of temporal simultaneity depends on several factors, of which the most important are stimulus intensity, redundant information, and selective attention (Shi, Hirche, Schneider, & Müller, 2008). From a visuo-haptic study by Shi et. al. it was shown that the points of subjective simultaneity decreased significantly under conditions of active motor control with concurrent visual feedback. Likewise, the just noticeable difference (JND) was narrowed by either active motor control or visual feedback (Shi et al., 2008).

Limited research is accessible from the literature and the data that is accessible is typically very product specific. Possibly because most research is conducted by companies and thus kept confidential for competitive purposes. However, such research does hold a considerable potential value. For instance, it is reasonable to assume that the sensitivity of certain sensory modalities can be reduced through affective ventriloquism. Looking at a press button an example could be that users would not perceive the variation in a click-sound as strongly if the haptic feedback is strong enough to dwarf the auditory sensation, or vice versa.

4.4 Future Work

For future work there are many aspects of perceived quality, robustness, and psychophysics that could be valuable contributions to the field of perceptual robustness. Many such aspects have to do with the practical costs and benefits of utilizing a perceptual robustness approach in product development. On the cost side, the amount of resources required to generate useful data and maybe cost saving approaches for conducting the experiments could be worth investigating. On the benefits side, the usefulness of such data would have to be validated. There exists a large step between studying an isolated physical stimulus from e.g. the perception of colour and the significantly more complex sensory experience of a product design parameter, such as the colour of a part, where also geometries, adjacent colours, etc. will play a role. This is where multimodal perception becomes relevant. The perception of a product and the robustness of that perception can be exceedingly complex. Investigating the interactions between different modalities in a product context will be incredibly valuable, not only for the design of very similar products, but possibly also for other products that share just a few perceptual traits.

Lastly, the nature of identifying non-quality could be investigated. A hypothesis is that when identifying unintentional features of a design, a reference is used. This reference could be based on symmetry, geometrical shapes, colours or other features of the design that creates an expectation for how the rest of the design should look. These references are likely to be formed on basis of a combination of the perceived design and prior knowledge. If these mechanisms were better understood they could be used for achieving a more robust product perception and more overall appealing designs.

5 Conclusion

The majority of the findings presented in this article are very intuitive and most designers would probably come to the same conclusion with or without the quantitative information given in this article. In this regard, the paper provides theory to support current practices and intuitions. However, many design aspects are not very intuitive and the quantitative measures presented here can be a very useful guide. Furthermore, knowing the psychophysical mechanisms in play for a given design will help make prioritizations and are likely to inspire ways of improving the design. Lastly, in all cases it is useful to have a theoretical and quantitative background for making design decisions as it provides a more data driven design process where less is left to chance, and the awareness of important design aspects are brought to the attention of designers and managers. These considerations allow marketing and product design to have a role to play in the robustness of the product being developed, currently left to the engineering and production teams.

Thus, this article emphasises that psychophysics can provide valuable inputs for designers. Of course, producing robust products is only one of many priorities. For business to customer products, often the overall appeal of the product would be a primary concern and robustness is of less importance compared. However, recent incidents with product recalls and catastrophic market failures have shown that a robust design is always preferable.

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Applying Perceptual Robust Design: A Case Study

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Abstract
In manufacturing, a quality product is often defined as a product that complies with specification limits. To achieve this, the company must be able to handle incoming variation and reduce or mitigate it if necessary e.g. by implementing robust design methodology. A branch of robust design is perceptual robust design. Where robust design typically would consider the functional performance of the product the target for robustness optimization, perceptual robust design targets the perception of the functional performance of the product. In this article a case study is presented to show how the design of an injection device can be optimised for maximum perceptual robustness of the loudness of a click sound generated during use. The results showed that the robustness could be improved by up to 14.74%. However, as the optimum for perceptual robustness was found to overlap with the optimum for functional robustness, only up to approximately 2.2% out of the 14.74% could be ascribed solely to the perceptual robustness optimisation.

Keywords: Robust design, perceived quality, psychophysics

1 Background

Reminders of the importance of designing robust products are all around us. In the news we hear about call-backs after catastrophic incidences related to product failures and at home we experience how the home button of our new smartphone rattles more than the one we saw on display in the store, or how the bottle cap for the soda was weirdly loose, making us wonder if it was properly sealed.

These are all incidences that are closely linked to our overall perception of a product and in particular the quality of those products. Ultimately, deciding whether we want to buy or rebuy the products, which of course is of great concern to the industry and the product design engineers. There are many sources of variation that ultimately leads to the variation we experience in the products we surround ourselves with (Christensen 2012). Some sources apply in the production phase, some in the use phase, but common for them all is that they change the objective performance of the product.

To mitigate or avoid undesirable variation in product performance a number of principles exists (Ebro and Howard 2016). One category of principles is robust design. Traditionally, robust design aims at designing products that are insensitive to variation, meaning that given a fixed amount of ingoing variation a robust design will produce less outgoing variation than a non-robust design.

In this contribution, an addition to the robust design theory called perceptual robust design is applied in a case study. The purpose of the case study has been to investigate the applicability and usefulness of the approach. How the perceptual approach to robust design fits the remaining robust design theory was described in (Howard et al. 2017). Furthermore, an introduction to the theoretical basis of perceptual robust design in a product design context was introduced in (Pedersen and Howard 2017).

The approach, focuses on the perception of product performance rather than the objective performance, and utilises the blind spots of the human perceptual system to make the design more perceptual robust. The robustness is therefore manifested in the ability to mask variation in the objective product performance. To describe the translation between objective product performance and the perception hereof the approach make use of psychophysical models, which are available in the literature for many different stimuli.

As an example, consider the task of choosing a colour for a new product. To ensure the best possible perceived product quality the colour should be chosen such that variation is less likely to be noticed. Consulting the literature it is revealed that the human visual system is able to differentiate between far more nuances of green than red (Bhoyar and Kakde 2010). It is therefore reasonable to assume that a red product will be more perceptually robust in terms of colour perception. This could, for instance, mean that the fading of the product colour over time would be recognized later for a red product than for a green product.

This perceptual approach to robust design have only received little attention in the literature and no consolidated body of theory related to perceptual robust design have been identified. However, several contributions within a wide range of scientific fields operate with the term “perceptual robustness”. Namely, within hash functions for image and audio files (Monga 2010; Yan Zhao et al. 2013; Kıvanç Mıhçak 2011; Karsh, Laskar, and Richhariya 2016). Here, “perceptual robustness” refers to the hash functions’ design, where perceptual features are central as opposed to cryptographic hashing which rely on avalanche effects (Goyal, O’Neill, and Rao 2011). The meaning of perceptual robustness is therefore slightly different in this context and following this literature is of little relevance to perceptual robust design.

Perceptual robustness is also mentioned in literature addressing the robustness of multimodal interface design (Dumas, Lalanne, and Oviatt 2009; Oviatt 2003). However, this literature has a slightly different agenda as it focuses on the elimination of recognition uncertainty. Depending on the product functions in focus this could overlap with the issues usually addressed with robust design, but often the recognition of interface feedback would focus more on the cognitive processes than the sensory or perceptual processes.

The most relevant use of perceptual robust design was found in the perceived quality literature, which supported the argumentation for the relevance of perceptual robust design and helped scope the research. In addition the field of perceived quality introduces the notion of visual robustness (Forslund, Dagman, and Söderberg 2006; Forslund 2008). Visual robustness have been defined as “(…) the ability of a product’s visual appearance to stimulate the same visual product experiences as the nominal (perfect) design, despite small variation in its visual design properties” (Forslund 2008). This definition expresses the same goal as for perceptual robust design. However, the goal of perceptual robust design is to provide a basis that can be used across all sensory domains. Furthermore, perceptual robust design relies on psychophysical models to explain the translation between stimuli and perception. Therefore, the fundamental approach of visual robustness differs slightly from that of perceptual robust design.

In the following sections the basic theory behind psychophysics will be briefly presented followed by an introduction to the case study.

1.2 Psychophysics

To explain the mechanisms of the human sensory, perceptual, and cognitive system, the field of psychophysics was introduced in the mid-19th century, mostly regarded as a branch of psychology.

The study of the processes of the mind can be investigated on three overlapping levels - low-level, mid-level, and high-level processes. In short, low-level processes can be described as sensory information gathering, mid-level processes as perceptual information synthesis, and high-level processes as memory and decision-making processes (Sarris 2006).

With this definition of the processes of the mind, this paper will mostly be concerned with the low- and mid-level processes. That is, the processes that describe what happen between the emission of physical stimuli and the forming of a percept in the mind.

In particular, Stevens' power law and Weber's law will be addressed, which describes the sensation magnitude of a physical stimulus and the human ability to detect differences in stimulus intensity, respectively (Zwislocki 2009). The mathematical expression of each of these laws will form the basis for the case study analysis. Further information on the laws and the analysis will follow in Section 2.

1.3 The Case Study

The case study is performed to show in detail how psychophysical information can be turned into valuable design inputs. Many considerations and trade-offs that will have to be made by product managers will not be quantified in this article.

Specifically, the case study investigates how to increase the perceptual robustness of the loudness of the dose selection click sound from the Novo Nordisk FlexTouch® injection pen.

The FlexTouch® pen is the latest generation of prefilled injection pens developed by Novo Nordisk A/S. The overall design of the pen can be seen in Figure 1.

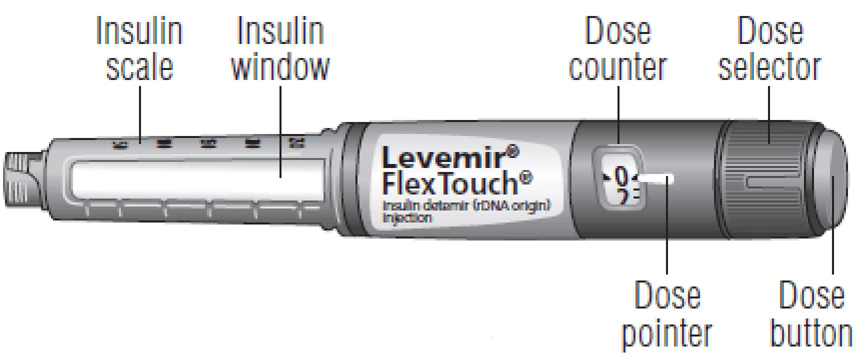

Figure 1. Overview of FlexTouch® basic functionalities (RXList 2016).

In this case study the focus will be on the click sound generated from turning the dose selector. For every unit dialled, as displayed in the dose counter, a click will sound. The sound is intended to help users keep track of the dose they have dialled, and is therefore linked to both usability and safety. Also, as the sound is repeated for every unit dialled for every dose injected, it is a central part of the sound aspect of the product.

The click is generated by two parts in the pen, the clutch, which can be described as a teethed wheel, and the ratchet, which has a click arm attached in the end. When a dose is dialled the clutch is turned. One unit corresponds to the distance between two valleys between the teeth of the clutch. By turning the clutch the click arm is pushed backwards by the teeth of the clutch resulting in a click sound when the click arm head passes a tooth and swings back hitting the valley area. The impact generates the vibrations of pen parts that give rise to the pressure waves which the user will experience as the click sound.

A sound can be described by a few characteristics, which determines how humans experience the sound. Pitch and loudness are the most central aspects of the human perception of sound. Pitch is determined by the frequency of the wave signal and loudness is determined by the intensity. However, some frequencies contribute more to the perception of loudness than others, and some frequencies cannot be heard at all. Usually intensity is described as a sound pressure level (SPL) in decibels. To describe the human experience of loudness an A-weighting is often applied to the signal. The A-weighting ensure that the signal is emphasised or attenuated depending on the sensitivity of human hearing at different frequencies. Therefore, measurements will be measured in dBA SPL, in the following just denoted dBA.

The study has been divided into three stages. First, psychophysical theory was consulted for information that could serve as general design guidelines, which is described in Section 2. Next, an experiment was performed to investigate product specific aspects of the problem, described in Section 3. Following, a transfer function was derived to identify the design parameters to address to increase the perceptual and functional robustness of the dose selection click sound of the product, which is described in Section 4. Finally, in Section 5, an analysis is performed to quantify the impact of the functional and perceptual increase of product robustness.

2 Theoretical Design Inputs

In this section psychophysical theory will be consulted to investigate if any existing laws or theories can help identify an optimal loudness of the dose selection click sound for making it more perceptually robust.

In (Pedersen and Howard 2017) an overview of psychophysical laws and brief discussions of how they can be used in a robust design context is presented. Reviewing the laws proposed in this article two general laws for describing sensation magnitude and just noticeable differences (JNDs) were identified as relevant to the case study. These laws, also known as Steven’s Power Law and Weber’s law, respectively, will be analysed in the following.

2.1 Steven’s Power Law

Stevens’ power law describes the sensation magnitude as a function of stimulus intensity through the following power function. Using design terminology it can be viewed as a transfer function given by:

$$(1) \quad \psi(I) = kI^a$$

Where ψ is the subjective sensation magnitude, I the magnitude of the physical stimulus, k is a dimensional constant that depends on the units used, and a is a power exponent depending on the stimulus type (Zwislocki 2009). A sensation can be described in many ways and it is important to take note that Steven's Power Law is only describing the sensation magnitude.

The value of the power exponent, which depends on the stimulus type, can generally be divided into three categories: $a > 1$, $a = 1$, and $1 > a > 0$. For $a = 1$, $\psi(I) = kI$, meaning the sensation magnitude is directly proportional with the stimulus. For $a > 1$, the sensation magnitude will accelerate as the stimulus increase which can be described by an upward concave curve. Reversely, for $1 > a > 0$, the sensation magnitude will decelerate as the stimulus increase which can be described by a downward concave curve.

In a perceptual robust design context this means that for $a = 1$ any fixed change in the stimulus will be perceived as an equally large, or small, change in the sensation magnitude, regardless of the original intensity of the stimulus, meaning the robustness of the sensation magnitude is the same regardless of the stimulus intensity. For $a > 1$, however, as the stimulus increase any change will result in an increasingly larger change in sensation magnitude. Therefore, in terms of the robustness of the sensation magnitude it is a smaller-the-better situation. Oppositely, for $1 > a > 0$ a larger-the-better situation will apply.

Looking at the data reported for loudness sensation magnitude as a function of sound pressure level (SPL) an exponent value of 0.67 was reported by Stevens himself (Stevens 1957). With a value in the $1 > a > 0$ range Stevens' power law therefore suggests a larger-the-better situation would apply. However, here it should be noted that Stevens' results were based on a 300 Hz pure tone signal, which is different from the more complex frequency distribution of a click sound.

2.2 Weber's Law

Weber's law states that the ratio between the JND and the stimulus intensity is given by a constant called the Weber fraction. Weber's law is given by:

$$(2) \quad \frac{\Delta I}{I} = k$$

Where ΔI is the JND, I the reference stimulus, and k is a constant (Zwislocki 2009). $\frac{\Delta I}{I}$ is here what is called the Weber fraction. The Weber fraction can also be regarded as a percentage, namely the percentage of the reference stimulus required for a change to be noticeable.

Weber's law has some limitations that should be considered when using it in a design context. Many instances have been identified where the reference stimulus and JND ratio is not constant. Such instances, have mainly been encountered when investigating very weak or strong signals, or complex signals containing more than one form of stimulus. (Kundu and Pal 1986)(McGill and Goldberg 1968).

A consequence of Weber's law is that strong signals always will be more robust to fixed changes. However, to what degree this applies will vary. Experimental data from (Teghtsoonian 1971) suggests a Weber fraction of 0.04 for pure tone sound pressure levels, meaning that a 4% change of the sound pressure level is required for it to be just noticeable. To exemplify, a 20 dB SPL signal would require a 0.8 dB SPL change for it to be noticeable, where a 40 dB SPL signal would require a 1.6 dB SPL.

Summarising the findings from the analysis of Stevens' power law and Weber's law they both agree that the stronger the reference stimulus the larger the JND and the more perceptually robust the SPL signal will be.

3 Loudness JND Experiment

The theoretical analysis suggests that the larger the SPL the better in terms of perceptual robustness of the sound. However, the experimental data used in the literature was based on pure tone signals which is different from the broad-spectrum click sound of interest in this case study. Furthermore, the many noise factors introduced in an everyday setting in which the product would typically be used, might also influence the perceptual tendencies. Therefore, an experiment was designed to validate if these findings would also apply to the dose selection click sound of a Novo Nordisk FlexTouch® pen in an everyday setting.

The hypothesis tested in the experiment was that the JND for the dose selection click sound of a FlexTouch® pen would change proportionally to the A-weighted SPL, in a noisy environment. Meaning the aim was to investigate whether Weber's law holds true under the given circumstances. In the following sections, first the equipment and experimental method is described along with a description of the execution. Afterwards the results are presented and briefly discussed.

3.1 Experimental Method

To investigate the JND of a click sound a number of psychophysical experimental method exists. For this study the method of constant stimuli was chosen. Other methods such as the two-alternative forced choice method might have produced less biased data (Pelli and Farell 2010), but given the aim of the study, a certain level of systematic errors were acceptable.

The method of constant stimuli falls under the category of judgments methods, meaning the test subject is being asked to make a judgment about a sequence of stimuli. More specifically, the method of constant stimuli entails that the test subject is presented with different levels of stimuli in a random order and is then asked to judge whether a criteria is meet or not (Pelli and Farell 2010; Ehrenstein and Ehrenstein 1999).

For this study the stimulus was a sound recording of a click sound and the test parameter was the A-weighted SPL of the click sound, which corresponds to the perception of loudness. The criteria to be judged was whether the test subject could hear a difference between a reference click sound and a second click sound played subsequently. The subsequent click sound was played at five different levels of amplification (difference levels), 0 dB, 3 dB, 6 dB, 9 dB, and 12 dB, where a 3 dB amplification equals a doubling of the volume of the signal. These levels had been identified in trial runs and chosen to approximately represent the whole spectrum of 0 to 100% percent identification of differences in signal loudness. As the experiment set out to investigate what happens with the JND as volume levels change, three different levels for the reference clicks (reference levels) were chosen at 50 dB, 65 dB, and 80 dB.

Each difference level where presented five times for the test subjects in a random order, meaning a total of 25 presentations where played for each reference level. With three reference levels a total of 75 data points were produced for each test subject.

3.2 Experimental Setup

In the following the equipment, the setup and the execution of the experiment is described in a chronological manner. The preparations for and execution of the experiment can be summarised by the following steps:

1) Calibration of equipment
2) Recording of click sound
3) Determining sound levels
4) Test subject preparations and instructions

The experimental setup included Sennheiser HD 380 Pro headphones, Focusrite Scarlett 2i2 soundcard, and a PC running Windows 7 and Matlab. The calibration of the setup and the recording equipment were performed using a Norsonic Nor140 sound analyser and a Norsonic type 1251 sound calibrator.

To record the click sound a Brüel & Kjær type 4100 head and torso simulator microphone was used along with a Novo Nordisk FlexTouch® injection pen. The recordings were made in an anechoic chamber to reduce background noise. Here the injection pen was held in front of the navel region of the torso while clicks were generated by dialling a dose, pausing in between each click. Following editing was performed using Audacity® sound editing software, which included noise reduction and the removal of dithering. The resulting click sound used in the experiment was an average of several clicks sounds, which helped cancel out noise and create a more reproducible click sound. This click recording was used to produce 25 sound files consisting of two clicks were the second click was a 0 to 25 dB amplification of the first click. Each file consisted of the following elements:

1) 0.1 s silence
2) First click sound
3) 0.2 s silence
4) Second click sound
5) 0.1 s silence

Having produced the sound files to be used as the experimental stimuli, appropriate difference and reference levels had to be identified. The reference levels where picked in order to represent as wide a spectrum as possible without having the loudest amplifications becoming uncomfortable and the lowest becoming inaudible in a noisy environment. To satisfy these conditions three levels were chosen at 50 dB, 65 dB, and 80 dB. Following, difference levels were chosen at 0 dB, 3 dB, 6 dB, 9 dB, and 12 dB. As mentioned earlier, these levels had been identified in trial runs and chosen to approximately represent the whole spectrum of 0 to 100% percent identification of differences in signal loudness. As the experiment set out to investigate whether Weber's law holds true in everyday settings, the experimental location was chosen so that a fairly constant level of office environment noise was present. Measurements showed an approximate noise level of 42 dB.

In total seven test subjects participated, six male and one female, with ages ranging from 27 to 46 years. All self-reported a normal hearing. The experiment was conducted in a small meeting room around a table. Before the actual experiment, test subjects were told that they would be listening to three times 25 double clicks, where the first click would be a reference click and the second would be identical or a louder version of it. After each playing, test subjects were asked to report whether they thought the clicks were identical or different.

3.3 Experimental Results

The results of the experiment were a total of 525 data points, 75 for each participant, stating either "identical" or "different" for a stimulus. With three reference levels and five difference levels 15 different stimuli where investigated. In Fig. 2 the sum of all responses are shown. Each curve is a sum squared error (SSE) fitted sigmoid function, which represent a reference level. The data points used to fit the curves are represented by the circle and plus signs. Difference levels are represented on the horizontal axis. On the vertical axes the percentage of responses registering a difference is shown.

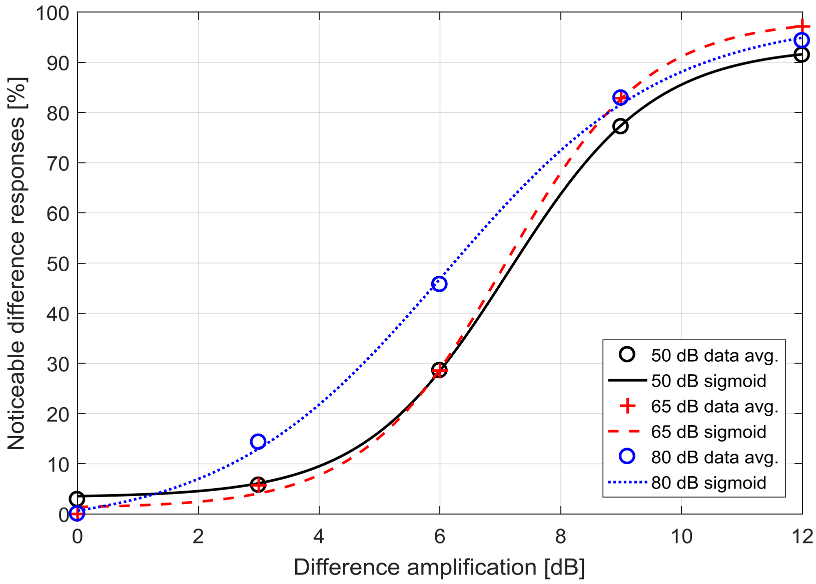

Figure 2. Plot showing data from JND experiment. Sigmoid curves are fitted to the averages of noticeable difference responses from all test subjects.

All reference levels follow the same s-shaped curve. However, for the 80 dB reference level there seems to be slightly higher rate of "difference" responses than for the 3 dB and 6 dB difference levels. With this observation being most distinct for the 6 dB difference level a paired-sample t-test was performed between the mean of the 50 dB and 65 dB reference level and the 80 dB reference level. This returned a p-value of 0.2 meaning the responses for the 80 dB level was not significantly different from the two lower ones.

Since there is no statistically significant difference, Weber's law s holds true for the 6 dB difference level. With the 6 dB level displaying the largest differences it can therefore be concluded that Weber's law holds true for all investigated levels based on plot investigations.

4 Transfer Function Experiment

Having found that the JND for the dose selection click sound of a FlexTouch® pen increase as the SPL increase both by consulting existing data, and by generating our own more product specific data, a transfer function was then derived to identify the design parameters (DPs) controlling the loudness of the click sound.

4.1 Experimental Method and Setup

In a previous study by (Jensen et al. 2015) click sound data for a click mechanism conceptually similar to that of a Novo Nordisk FlexTouch® injection device, but scaled up, was obtained through a fractional factorial designed experiment. The experiment investigated how design parameters of a click arm and toothed racks influence an A-weighted SPL of the click sound generated by dragging the click arm over the toothed rack (see Fig. 3). The A-weighting, was used to better approximate the human experience of loudness.

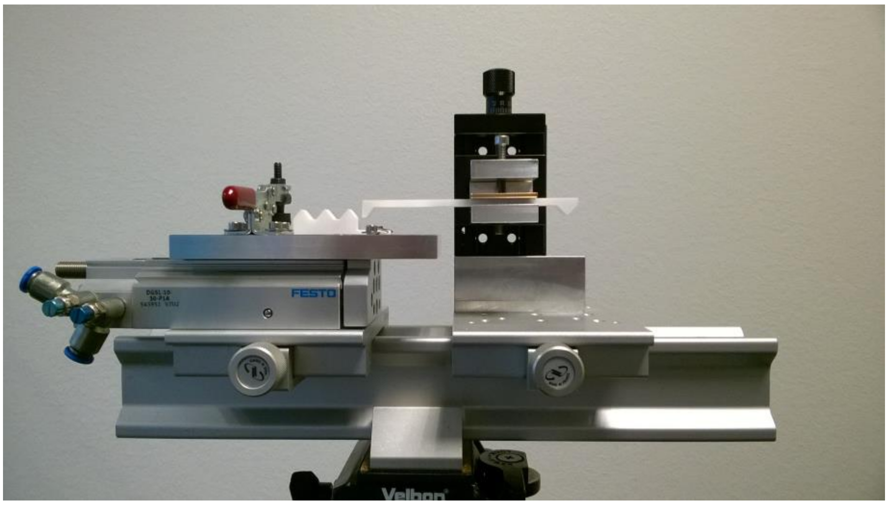

Figure 3. Experimental setup (Jensen et al. 2015)**.**

Further information on the experimental setup and data, and the limitations that applied, can be found in (Jensen et al. 2015).

To better describe the non-linear behaviour of the design parameters investigated in (Jensen et al. 2015), a more comprehensive study of non-linear behaviour of the selected parameters was carried out. This was done with another DoE experiment using the same equipment and facilities as in (Jensen et al. 2015). The dimensional limits for the DPs specified in (Jensen et al. 2015) also applied in the present experiment. However, two additional DoE levels evenly spaced between the limits were added to the experiment to better investigate the non-linearity. For the experiment nine parameters and interactions were chosen based on their design relevance and their impact on the SPL found in (Jensen et al. 2015). 44 combinations of these nine terms were investigated in the experiment, with five runs for each combination.

4.2 Experimental Results

Initially, the parameters were described with categorical levels. Therefore, an output value for each of the four levels for each parameter was produced. The values are shown as prediction profiles in Fig. 4. The unit on the vertical axis is dBA and the unit on the horizontal axis for each of the seven parameters are mm and degrees, respectively.

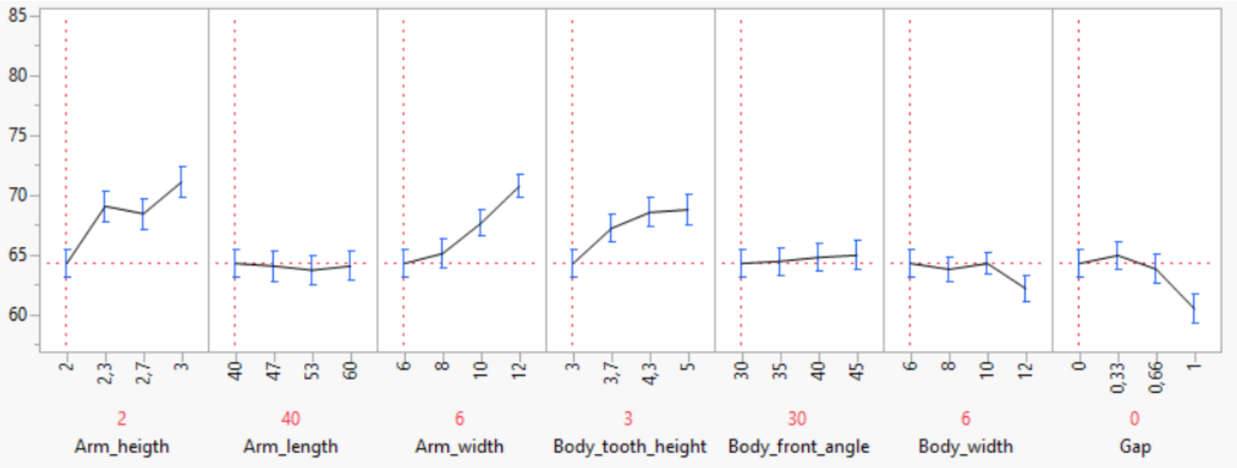

Figure 4. Prediction profiles for the seven parameters defining levels categorically.

When looking at the profiles it seems that arm length and body front angle do not have a large impact on the response. The body width also seemed to have a minor influence except at 12 mm. All parameters seemed to have a close to linear sensitivity except for the gap that seemed to behave exponentially.

The parameters were then changed from categorical to continuous, which enabled the possibility to make regressions based on linear or exponential behaviour. First linear behaviour for all parameters was assumed and body front angle was left out as a consequence of its very low influence. Since the gap was not clearly linear, a second modification of this prediction was made, assuming that the impact of the gap was exponential. This modification led to an improved total R-squared value for the experiment, increasing it from 0.859 to 0.889. As the new gap parameter also was statistical significant it was concluded that the gap was better explained when adding a second order term.

The continuous parameter profiles are illustrated in Fig. 5. The angles of the lines illustrate how large an impact the parameters are predicted to have on the response. Arm width appears to have the largest impact while body width seems to be the only parameter with no influence. Opposite to the categorical prediction profiles (Fig. 4) it seemed that the arm length had a significant impact.

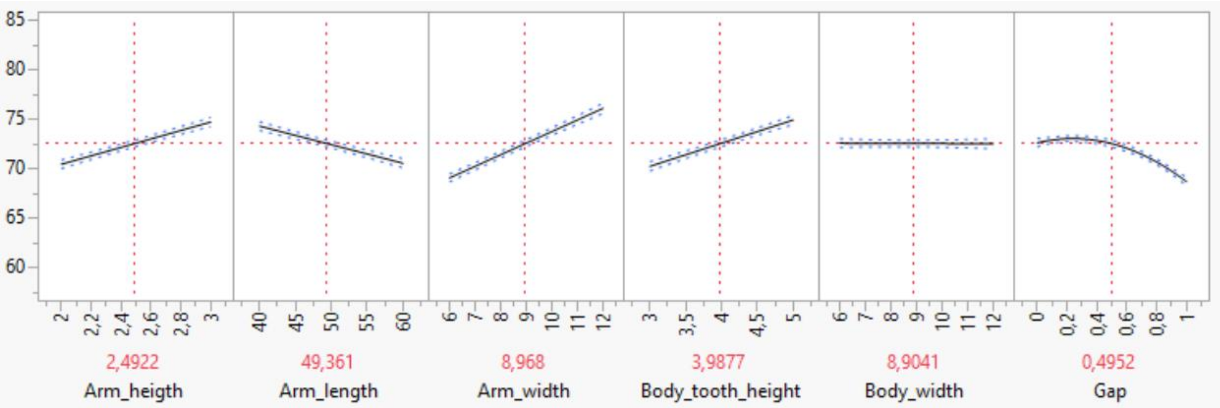

Figure 5. Regression models for six parameters defining levels on a continuous scale.

The sorted parameter estimates, are listed in Table 1. As shown, all results except for body width were statistical significant. This fits well with the fact that body width was only included due to the interaction with arm width.

Table 1. Estimates, standard error, t-ratio, and prob(t) values for each chosen parameter and interaction.

Sorted Parameter Estimates				
Term	Estimate	Std Error	T Ratio	Prob>[t]
Arm width	1.1688905	0.051304	22.78	<0.0001
Arm height	4.2608361	0.285083	14.95	<0.0001
Body tooth height	2.3387773	0.159559	14.66	<0.0001
Gap	-3.839131	0.294153	-13.05	<0.0001
Arm length	-0.187436	0.015272	-12.27	<0.0001
(Gap-0.49521)* (Gap-0.49521)	-7.493183	1.003834	-7.46	<0.0001
(Body width-8.90411)*(Arm width-8.96804)	0.1190424	0.023072	5.16	<0.0001
(Arm length-49.3607)*(Arm height-2.49224)	-0.174448	0.037281	-4.68	<0.0001
Body width	-0.010009	0.052992	-0.19	0.8504

The estimates listed in Table 2 equals the coefficients of the transfer function with the unit dBA/mm. This means that if arm width is increased 1 mm then the response is increased with 1.16 dB. Arm height is having the largest impact in dB/mm, which can be explained by the large increase of stiffness when only making the beam a little bit thicker. The impact for arm length in dB/mm is very small (0.187), but since the arm length often can be changed a lot it can still be a beneficial parameter to use for adjustment of the sound pressure level.

Based on the results from the non-linear experiment, a transfer function between the relevant DPs and the A-weighted SPL of the click sound was derived using SAS JMP software. The resulting transfer function is given by equation 1:

$$(1) \quad L(DPs) = 53.40 + 4.26A - 0.19B + 1.17C + 2.34D - 0.01E - 3.84F + (B - 49.36) * \big((A - 2.49) * -0.17\big) + (E - 8.90) * \big((C - 8.97) * 0.12\big) + (F - 0.50)^2 * -7.49)$$

Where, $L = Loudness\ [dBA]$, $A = Arm\ height\ [mm]$, $B = Arm\ length\ [mm]$, $C = Arm\ width\ [mm]$, $D = Body\ tooth\ height\ [mm]$, $E = Body\ width\ [mm]$, and $F = Gap\ [mm]$.

4.3 Model Verification

To verify the experimental findings another experiment was conducted to test if the transfer model could predict the SPL of the FlexTouch® pen. Compared to the previous experimental setup the DP dimensions of the FlexTouch® pen were outside of the investigated range. Furthermore, the mechanism in the FlexTouch® pen was rotational and covered by a housing that was anticipated to absorb some of the energy. Due to these differences some discrepancies were expected.

For the experiment the previous setup was replicated as much as possible, meaning the recording equipment, the facilities, the distance from the moving parts to the microphone, and the recording software all were the same. However, the FlexTouch® pen was handheld and the turning of the dose selector was also done manually.

As it appears from Table 2, the experiment included 5 runs with a mean SPL of the click sounds of 51.21 dBA and a standard deviation of 0.68 dBA.

Table 2. Summary statistics for the model verification.

Summary statistics	
Mean	51.206
Std Dev	0.6824441
Std Err mean	0.3051983
Upper 95% Mean	52.053366
Lower 95% Mean	52.358634
N	5

Using the transfer function and the actual dimensions of the FlexTouch® pen the SPL of the click sound was predicted to be 50.62 dBA. The resulting discrepancy between the predicted value and the experimental value was 0.61 dBA, which is much less than anticipated. However, the fact that the experimental and predicted values were relatively close indicated that the model was likely to be suitably accurate for the purpose.

5 Impact of Perceptual Robust Design

To quantify the impact of perceptual robust design four design situations were compared. The first design was the original design where DPs were measured from the parts, and loudness was predicted using $L(DPs)$. The second design was optimised for maximum functional robustness, where DPs were found by optimising for the minimal standard deviation of $L(DPs)$. The third design was optimised for maximum perceptual robustness as a function of loudness. To determine the pertaining DPs two consecutive optimisations were performed. First, the standard deviation of $\psi(L)$ was minimised to verify that maximising loudness also maximised perceptual robustness, and then $L(DPs)$ was maximised to determine the DP values. The last and fourth design was optimised for maximum perceptual robustness as a function of the DPs, meaning DPs were optimised for the minimum standard deviation of $(\psi \circ L)(DPs)$.

Using the commercial software VarTran®, optimisations were performed with IT13 grade tolerances on the original design. First, the optimisations were run with no constraints to the inputs or the outputs. The results are shown in Table 3. For $\min \sigma(L(DPs))$ all DPs have a nominal optimum, except for D, where the partial derivative is a constant and all values are equally robust. For $\min \sigma(\psi(L))$, it is found that larger/smaller-the-better applies for all DPs, except F. Lastly, for $\min \sigma((\psi \circ L)(DPs))$ both the sensitivity introduced by $L(DPs)$ and $\psi(L)$ were taken into account. Here the same optimums as for $\min \sigma(L(DPs))$ applies, with the exception of D, for which larger-the-better applies.

Table 3. Design parameters for the original design and three designs optimised for maximum robustness without any limits to DP values.

Indicator	Solution space	1) Original design	2) $\min \sigma(L(DPs))$	3) $\min \sigma(\psi(L))$	4) $\min \sigma((\psi \circ L)(DPs))$
A – arm height	-∞-∞ mm	0.85 mm	1.37 mm	-∞ mm	1.37 mm
B – arm length	-∞-∞ mm	7.7 mm	74.42 mm	∞ mm	74.42 mm
C – arm width	-∞-∞ mm	2.3 mm	9.05 mm	∞ mm	9.05 mm
D – body tooth height	-∞-∞ mm	0.5 mm	Any value	∞ mm	∞ mm
E – body width	-∞-∞ mm	3 mm	-0.85 mm	∞ mm	-0.85 mm
F – gap	-∞-∞ mm	0 mm	0.24 mm	0.29 mm	0.24 mm
L - loudness	-∞-∞ mm	50.62 dBA	-23440.00 dBA	∞ dBA	∞ dBA
ψ – sensation magnitude	-	13.87	846.98	∞	∞
$\sigma(L)$		0.27445 dBA	0.054619 dBA	N/A	N/A
$\sigma(\psi)$		0.050361	0.001322	N/A	N/A

As evident from Table 3 many of the optimal values were impossible or unpractical for the design of a click mechanism. Therefore, constraints were applied to inputs and outputs. For the inputs the constraints were set at plus/minus 50% of the original dimension except for the gap which were set from 0-2.00 mm. For the output of the loudness a minimum was set at 0 dBA SPL which is the threshold of hearing and the maximum was set at 120 dBA SPL which is the pain threshold.

Having defined a solution-space, more realistic nominal values were found for all DPs, as seen in Table 4. Again, the optima for $\min \sigma(L(DPs))$ and $\min \sigma((\psi \circ L)(DPs))$ is similar with the exception of D, which should be maximised for maximum perceptual robustness.

Table 4. Design parameters for the original design and three designs optimised for maximum robustness with DP limits set at +/- 50% of original values.

Indicator	Solution space	1) Original design	2) $\min \sigma(L(DPs))$	3) $\min \sigma(\psi(L))$	4) $\min \sigma((\psi \circ L)(DPs))$
A – arm height	0.43-1.28 mm	0.85 mm	1.28 mm	1.28 mm	1.28 mm
B – arm lenght	3.85-11.55 mm	7.7 mm	11.55 mm	11.55 mm	11.55 mm
C – arm width	1.15-3.45 mm	2.3 mm	3.45 mm	3.45 mm	3.45 mm
D – body tooth height	0.25-0.75 mm	0.5 mm	0.25-0.75 mm	0.75 mm	0.75 mm
E – body width	1.50-4.50 mm	3 mm	1.50 mm	1.50 mm	1.50 mm
F – gap	0-2.00 mm	0 mm	0.24 mm	0.24 mm	0.24 mm
L - loudness	0-120 dBA	50.62 dBA	56.96-58.08 dBA	58.08 dBA	58.08 dBA
ψ – sensation magnitude	-	13.87	15.01-15.20	15.20	15.20
$\sigma(L)$		0.27445 dBA	0.25586 dBA	0.25586 dBA	0.25586 dBA
$\sigma(\psi)$		0.05036	0.044869 -0.045172	0.044869	0.044869

To further substantiate the impact of perceptual robust design, specification limits were compared on basis of two different assumptions regarding proportionality between appropriate specification limits and JND, and $\sigma(\psi)$, respectively.

Defining the original specification limits as $n_{old} \mp r_{old}$ the JND proportionality assumption assumes appropriate specification limits can be set at $n_{new} \mp \frac{JND_{new}}{JND_{old}} * r_{old}$. The one-sided part of the range can therefore be loosened by $100 * \left(\frac{JND_{new}}{JND_{old}} - 1\right)$ percent. Likewise, for the $\sigma(\psi)$ proportionality assumption appropriate specification limits are set at $n_{new} \mp \left(-\left(\frac{\sigma(\psi)_{new}}{\sigma(\psi)_{old}} - 2\right)\right) * r_{old}$. The one-sided part of the range can therefore be loosened by $100 * \left(-\left(\frac{\sigma(\psi)_{new}}{\sigma(\psi)_{old}} - 1\right)\right)$ percent.

Table 5. The impact of design situation 1-4, quantified in terms of potential for loosening requirement specifications.

	JND (4% of L)	Δr_{new} for JND (%)	$\sigma(\psi)$	Δr_{new} for $\sigma(\psi)$ (%)
1) Original design	2.0248 dBA		0.05036	
2) $\min \sigma(L(DPs))$	2.2784 dBA	12.52-14.74%	0.044869 -0.045172	10.30-10.90%
3) $\max L(DPs)$	2.3232 dBA	14.74%	0.044869	10.90%
4) $\min \sigma((\psi \circ L)(DPs))$	2.3232 dBA	14.74%	0.044869	10.90%

In Table 5 the percentage change of specification limits made possible by the robustness optimisations is shown. For $\min \sigma(L(DPs))$, L and $\sigma(\psi)$ are listed as a range as the value of design parameter D can take any value in the solution space. The difference in appropriate specification limits are therefore also given by a range. For $\min \sigma(\psi(L))$ and $\min \sigma((\psi \circ L)(DPs))$ a nominal value for L is found and the analysis show that specification limits can be loosened by 14.74% based on the JND proportionality assumption. For the $\sigma(\psi)$ proportionality assumption values for $\sigma(\psi)$ exist for all design situations. The analysis shows that specification limits can be loosened by 10.90%.

6 Discussion

In the following, the results and findings of the paper will be discussed starting with the theoretical background, then the experimental design inputs from the JND experiment, then the functional transfer function identifying relevant design parameters, and lastly the impact of perceptual robust design.

6.1 Theoretical Background

In the present case study theoretical design inputs were used to predict perceptual trends. More specifically Stevens' power law and Weber's law were used to establish whether the design was dealing with a smaller- or larger-the-better situation in terms of perceptual robustness. Two issues here should be addressed. Firstly, the case product click sound, comprising a wide range of frequencies, was different from the pure tone signal used in the psychophysics literature. Secondly, when investigating sensation magnitude or JND the test conditions are typically highly controlled with very little noise. The environment when purchasing or using the case study product, on the other hand, is likely to introduce a wide variety of noise factors. Both issues were addressed by the JND click sound experiment.

6.2 Experimental Design Inputs

The results of the loudness JND experiment showed that Weber's law of a constant ration between the JND and stimulus signal strength holds true, also for click sounds in noisy environments. This supported the hypothesis that the click sound would be made more perceptual robust by increasing the SPL. No distinctive sources of noise were identified, but with no monitoring of the noise levels throughout the experiment this might have fluctuated between test subjects and stimuli. If high levels of noise had been present it might have caused a masking effect of especially the low volume reference levels. Despite not being statistical significant, the higher frequency of "difference" responses for the 80 dB reference level, might be explained by exactly this phenomenon.

Furthermore, the hearing capability of the test subjects were assessed by self-reporting, which potentially could allow for some fluctuations. However, as test results were fairly similar with no distinct outliers it seems reasonable to assume that these self-reportings were good estimates.

6.3 Functional Transfer Function

Concerning the functional transfer function between DPs and loudness, several sources of errors were present. The most important of which were identified as the parts of the pen not represented in the DoE and the differences in materials and size between DoE test parts and the FlexTouch® pen. In relation to the scaling problem it is also likely that the accuracy of the model would worsen outside of the dimensional ratios investigated in the experiment. How much of an impact these sources of error had on the results was hard to quantify. However, given the fairly close prediction of the FlexTouch® click sound it seems reasonable to assume the overall tendencies of the results are accurate. Having defined the solution space as +/- 50% of the original dimensions it was ensured that the ratio between DP dimensions represented in the transfer model were considered.

6.4 Impact of Perceptual Robust Design

Using the evaluation method described in Section 5 the results show that by optimising for perceptual robustness the specification limits can be loosened by 10.90 or 14.74%, depending on the underlying proportionality assumption. Using the potential for loosening the specification limits as a measure of impact was chosen as it will be very individual what challenges the company is facing. Some will use the potential to increase the perceived quality of their product while others would allocate it towards problematic manufacturing tolerances. By quantifying the potential for loosening requirement specifications, the actual monetary benefit of the optimisation can be assessed on an individual basis.

However, the results raise a few questions. The unconstrained optimum for functional robustness and perceptual robustness as a function of loudness were very different. At the same time the optimum for perceptual robustness as a function of the DPs were almost identical to the optimum for functional robustness. This is explained by the fact that the sensitivity introduced by the functional transfer function is more significant than the one introduced by the perceptual transfer function. However, functional transfer functions will vary significantly from function to function and from product to product. Likewise, the psychophysical models will also vary from situation to situation. Not only will the Stevens' power law exponent or Weber fraction change, the perceptual solution space will also vary. For instance, the allowable loudness for the click when closing a battery compartment lid might be louder than for an injection pen dose selection click. Therefore, other case studies might show different results.

The problem could also be addressed analytically. When using Stevens' power law to determine the sensitivity of the perceptual process, the transfer function will always be a power function with the relevant exponent. The functional or mechanical transfer function on the other hand can take many forms depending on the product. If only nominal DP values are used as inputs to the optimisation it is possible to analytically predict which of the two transfer function that will dominate or if a compromise will be the overall optimum. If probability density functions are used as inputs, as in the present case study, it would require methods such as Monte Carlo simulations to make any predictions.

A final note that is important to emphasise is the intended use of perceptual robust design. In product development many different priorities must be considered. Depending on the context some might be central in one situation and negligible in another. Product robustness is one of these priorities and perceptual robust design is one of many ways of addressing product robustness. With little data being available from the literature it is hard to quantify when and to what extent it is meaningful to implement perceptual robust design. The purpose of this article was first and foremost to show how perceptual robust design can be implemented and secondarily to show the potential benefits. The case study only presented limited benefits from the perceptual robustness optimisation in comparison to a more traditional functional robustness optimisation. However, there is nothing to suggest other case studies would not produce even bigger improvements.

Future work will include additional case studies to generate data which can help quantify the impact of perceptual robust design and correlate it with parameters such as product characteristics, product categories, and market segments. Furthermore, the improvement of perceptual robustness achieved in case products should be validated in user studies. Many sources of errors are introduced when applying psychophysics data, obtained under ideal conditions, to more chaotic real life situations.

7 Conclusion

The case study has shown that perceptual robust design information by relatively simple means can be utilised in product design by consulting psychophysics theory, verifying findings, and constructing transfer functions to identify relevant design parameters.

The usefulness of the approach was assessed in terms of the potential for loosening requirements specifications. For this case study the optimisation resulted in a potential loosening of requirements specifications of close to 15%. Most of the potential originated from the mechanical robustness optimisation, but up to 2.2% could be traced back to perceptual robust design. For designs with a smaller potential for mechanical optimisations it is reasonable to assume the potential originating from the perceptual aspects would be even more pronounced.

In conclusion, perceptual robust design has shown a potential for increasing the robustness of products. It can therefore be considered an addition to the engineering designer's toolbox when aiming at increasing the robustness of products. However, additional case studies should be conducted to further investigate the general potential as well as the potential in relation to product or company specific parameters.

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ISBN: 978-87-7475-510-4

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ISSN: 0903-1685