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# Robust Product Development by combining Engineering Design and Designed Experiments

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To Daniel and Anette

# Abstract

Many successful industrial companies aim at improving product development in order to be competitive. This thesis is intended to make a contribution to the work of fulfilling this goal.

Rapid advances in technology in recent years have set new demands on product development. As a consequence, an increasing variety of products are built on heterogeneous technologies. Such products incorporate a mixture of technologies, often combinations of computer, electrical, and mechanical systems. Specialists from different engineering disciplines must co-operate to a greater extent than before in order to understand the products. Increased cooperation and heterogeneous technologies in products set high demands on *communication* and *systems integration* if product development is to deliver products with high quality, short lead times, and low cost.

This thesis presents research that advocates tools and methods for performance-related *robustness improvements in product development*. Robust products, or subsystems, are insensitive to disturbances and perform well under a wide range of conditions. It is found that robustness in product development increases multidisciplinary optimization, communication, and systems integration. Thus, robustness provides a solution to a number of important questions relating to systems integration and communication in product development.

The presented research consists of both theory development and practical implementations. The research in the appended papers provides: (1) a tool for customizing and designing company unique strategies; (2) an approach to problem solving and quality-related performance improvements by combining design object analysis with Axiomatic Design, Quality Control tools, and designed experiments; (3) equations for computing the Information content in decoupled design solutions; (4) equations for evaluating Quality Loss in Axiomatic Design; (5) a feature selection technique to improve robust classification in the multivariate domain; (6) a comparative study of two experimental methods for robustness improvements.

Two of the presented studies have been carried out in industry and the results have been implemented successfully. The remaining four studies were performed in an academic environment, although the results and simulations indicate industrial relevance when applied to real-life problems.

# Acknowledgments

Many individuals and organizations have helped in realizing this research.

In particular, I wish to thank Dr. Mats Nordlund at Saab Marine Electronics and Dr. Billy Fredriksson at Saab Technologies for being great mentors, both academically and professionally; Prof. Daniel Frey at MIT for being a splendid host, co-researcher and mentor during my years at MIT. Prof. Gunnar Sohlenius at KTH for sharing his knowledge and great visions; Prof. Bo Bergman at Chalmers University for introducing and guiding me through the world of Quality Technology and Statistics; and my fiancée Anette Qwärnström for coping with my long periods of absence and for keeping me in a happy frame of mind.

I also wish to thank:

My colleagues and co-researcher in the Robust Engine Group at MIT's Department of Aeronautics and Astronautics who taught me a lot about aircraft engine simulations and broadened my perspective on the applicability of probabilistic methods for robustness. My colleagues at the Department of Manufacturing Systems at KTH, as well as my former colleagues at the Department of Quality Technology and Management at LiTH, for interesting research discussions and discussions about life as a doctoral student in general, as well as helping me with practical matters. My colleagues at Saab Technologies for reminding me about the world outside the University and always stressing the importance of performing research that can be implemented practically; Tony Palm and Ann Snodgrass for helpful comments on my English. Nicholas Hirschi for helpful comments on my English in Papers A and B. My co-authors for fruitful research collaborations. Prof. Don Clausing for comments and suggestions for improvements on late manuscripts, stressing important research topics, as well as providing a holistic and industry-oriented view on the role of robustness in Product Development. Nicholas, Jens, Siddi, Gennadiy, Gaurav, Pung, and Alberto for turning the CIPD-lab into a truly stimulating working environment. Family and friends for support, good times in each other's company, and belief in this project.

Finally, this research has been financially supported by Saab Technologies, the Swedish Foundation for Strategic Research (SSF) through the ENDREA research program, Tekn. Dr. Marcus Wallenbergs Fond för utbildning i internationellt industriellt företagande, and the Royal Swedish Academy of Engineering Sciences (IVA) – Werthén fellowship. This support is gratefully acknowledged.

Boston, March 2001
Fredrik Engelhardt

# Contents

# Appended Papers

Appendix A Paper A: *Strategic Planning Based on Axiomatic Design*
Co-authored with Dr. Mats Nordlund
Presented at 1st International Conference for Axiomatic Design, MIT, Cambridge, USA, May, (2000)
Submitted to IEEE Transactions on Engineering Management.

Appendix B Paper B: *Improving Systems by Combining Axiomatic Design, Quality Control Tools and Designed Experiments*
Published in Research in Engineering Design, Vol. 12(4):204-219, (2001)

Appendix C Paper C: *Computing the Information Content of Decoupled Designs*
Co-authored with Prof. Daniel Frey, and Ebad Jahangir
Published in Research in Engineering Design, Vol. 12(3): 90-102, (2000)

Appendix D Paper D: *Computing the Economic Value of Robustness with the Axiomatic Design Framework*
Co-authored with Taesik Lee
Will be presented at, and appear in the proceedings of, the International CIRP Design Seminar, KTH, Stockholm, Sweden, June 6-8, (2001)

Appendix E Paper E: *Robust Manufacturing Inspection and Classification with Machine Vision*
Co-authored with Jens Häcker and Prof. Daniel Frey
Presented at CIRP's 33rd International Seminar on Manufacturing Systems at KTH, Stockholm, Sweden, May, (2000)
Accepted for publication in International Journal of Production Research

Appendix F Paper F: *The Role of the one-factor-at-a-time Strategy in Robustness Improvement*
Co-authored with Prof. Daniel Frey
Will be presented at, and appear in the proceedings of, the International CIRP Design Seminar, KTH, Stockholm, Sweden, June 6-8, (2001)
Submitted for international publication

Appendix G Introduction to the Taguchi Method

# 1 INTRODUCTION

## 1.1 BACKGROUND AND MOTIVATION OF THESIS

Many successful industrial companies choose product development as a means of acquiring, strengthening and maintaining market shares and competitive advantages (Christensen, 1997; Wheelwright and Clark, 1992). Rapid developments in technology during recent years have led to the introduction of many products built on heterogeneous technologies. Such products often comprise mixtures of software, electrical, and mechanical systems.

Today's expanded and mixed technology content in products entails greater complexity, thereby reducing the prospects of individual development engineers being able to understand every aspect of a product. Specialists from different engineering disciplines must co-operate to a larger extent than before. In recent years, the field of systems engineering has emerged in response to the increased need for coordination between heterogeneous technologies in product development (Rechtin and Maier, 1997).

Product development processes that were developed before the introduction of the Internet and the increased possibility of distributed development projects need to be updated in order to address current potentials and problems in product development. Great improvements were, and still are, achieved by applying customer-oriented as well as demand-oriented development and manufacturing process. See PRODEVENT (Sohlenius et al., 1976) and Quality Function Deployment (QFD; see Akao, 1990). An integration of QFD in product development is presented in Clausing (1994). Teamwork and other organizational aspects of product development continue to be greatly improved through the introduction of Integrated Product Development Teams and cross-functional teams (see for instance Ulrich and Eppinger, 1995). Concurrent engineering reduces lead times in product development by promoting parallel development tasks. A comprehensive summary of concurrent engineering is presented in Sohlenius (1992) and organizational aspects of concurrent engineering are discussed in, for instance, Fleischer (1997). Nevertheless, the new Internet technology and the rapid development of Computer Aided Design tools (CAD), together with ongoing globalization and the trend toward outsourcing, *further* increase complexity and speed in product development by theoretically enabling distributed product development to be carried out 24 hours a day in different parts of the world. See for instance Wallace (2000), Senin (1999), and Quinn (1999). To utilize the potential benefits of this distributed product development, further increases in communication are necessary in order to improve cooperation between distributed development teams (Maher and Rutherford, 1997). The significance of, and need for, improved communication in product development is also stressed by Martino et al. (1998) and McGrath (1996). The trends towards more complex products and a distributed development environment also increase the importance of integration of subsystems into products, integration development tools and methods, and coordination of development activities (Dabke et al., 1998; Rechtin and Maier, 1997; Ulrich and Eppinger, 1995). Furthermore, integration of subsystems into products is a significant aspect of design for assembly (see Pahl and Beitz, 1996) and modular design (see Erixon, 1998).

Hence, two areas of possible improvement for current and future product development, that are increasingly important topics, are *integration* and *communication*.

*Integration* of separately developed subsystems into products is improved through development of robust subsystems that are insensitive to disturbances from other subsystems as well as the external environment (Clausing, 1994). Tools for systems design are also needed for planning and carrying out integration tasks. These tools may consist of engineering design methods (see for example Suh et al., 1998). *Communication* in product development can, besides advances in hardware and software technologies, also be improved by the use of engineering design methods, and product development methods that create a common language and common routines in product development (see for instance McGrath, 1996; Pugh, 1991). Another more probabilistic way of looking at product development and communication is presented in Chen and Lewis (1999). Chen and Lewis use the robustness approach in order to improve flexibility and speed when dealing with problems of distributed and multidisciplinary optimization. They suggest communication with ranges of design solutions instead of single point design solutions in complex system design.

The above section has thus identified and indicated how robustness and a more probabilistic view of design relate to, and are important for, improved product development.

The term "product development" is throughout this thesis applied in a broad and concurrent engineering related way. Both the artifact itself and its manufacturing system must be developed and the overall term for these design efforts is, in this thesis, product development.

## 1.2 GOAL OF THE THESIS

The goal of this thesis is to present a number of contributions to improved product development. This high level goal can be broken down into more manageable sub-goals:

1. Contribute to improved performance-related product quality by providing methods and tools for the development of robust products.
2. Reduce lead time in product development by providing means for effective planning of the product development process.
3. Develop methods and tools that are of practical use in industry.
4. Create a learning experience for the author.

## 1.3 RESEARCH QUESTIONS

The high-level goals for the thesis stated in Section 1.2 are translated into the following research question:

*High-level research question*: What are generalizable ways of improving the product development process?

The corresponding high-level hypothesis is developed according to the needs and possibilities identified in Section 1.1 as follows:

*High-level hypothesis*: Adopting a more probabilistic view of design, stressing the importance of robustness in product development at both system and parameter level, and using designed experiments will improve performance quality and lead time in product development.

This high-level concept is then decomposed into a set of more delimited research questions aimed at clarifying certain aspects of the high-level research hypothesis and research question:

*Research question 1*: Can the engineering design theory Axiomatic Design, if used to help design a company strategy, also help design the corresponding strategic process?

*Research question 2*: Is it possible to combine Engineering Design and Quality Control tools with designed experiments in order to utilize *a priori* knowledge when dealing with problem solving in product development?

*Research question 3*: Is summing of the Information content of functional requirements in a decoupled design a proper way to calculate the aggregate

Information content of the design? [Information content is related to the probability of the success and is mathematically defined in section 3.3]

*Research question 4*: How can the economic value of robustness be expressed and evaluated by applying the tools and methods of Axiomatic Design?

*Research question 4.1*: What is the relationship between the form of Axiomatic Design's design matrix, i.e. coupled/decoupled/uncoupled, and the economic value of robustness?

*Research question 5*: How effective is the Mahalanobis Taguchi System (MTS) applied to multivariate robust classification compared to an approach that selects features for the classification based on a principal component transformation of the data set combined with a multimodal overlap measure (PFM)?

*Research question 6*: How effective is the one-at-a-time experimental strategy (OAT) compared with the Taguchi Method's orthogonal arrays in terms of: (1) signal-to-noise ratio improvement rate, (2) total signal-to-noise ratio improvement, (3) the number of experiments or calculations that have to be performed, as well as (4) the cost associated with changing factor levels?

These research questions (1-6) and their corresponding hypotheses are analyzed in Sections 3.1 - 3.6.

This thesis focuses on the research questions stated above. Therefore, many interesting observations from the appended papers are omitted. The reader is encouraged to read the papers for further details of the presented research.

## 1.4 DELIMITATION

This thesis focuses on product development issues within industrial companies. This broad scope is further delimited by focusing the research on the research questions, and more specifically:

- Developing a tool for strategic design and the design of processes, based on engineering design methodology.
- A method for improving product quality that combines design methodology, quality control tools, and designed experiments.
- An approach for computing the aggregate probability of success for design concepts in certain design situations.

- An equation for computing quality loss with the tools of Axiomatic Design, as well as developing a better understanding of the relationship between the form of Axiomatic Design's design matrix and robustness in terms of quality loss.
- A method for feature selection in robust multivariate classification.
- A comparison of two experimental strategies for improved robustness.

## 1.5 METHODOLOGY

Since product development is an "engineering science" consisting of elements from both social sciences and natural sciences, fundamentals of different schools of research philosophy are described below.

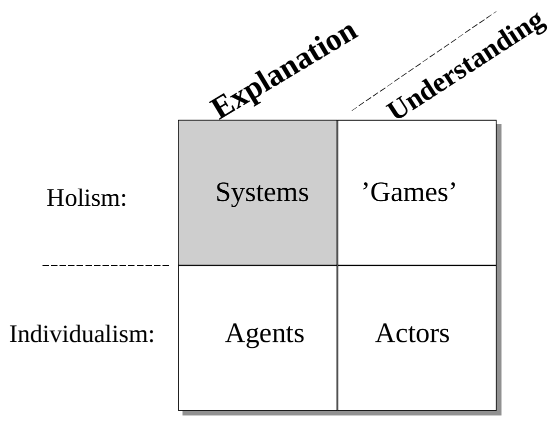


*Figure 1. Explanation and Understanding, two schools of scientific philosophy (Hollis, 1994).*

Hollis (1994) describes two major schools of scientific method for social science: the *Explaining* and the *Understanding* school. See Figure 1. Holme and Solvang (1997) discuss the same topic, but use the terms *quantitative* method and *qualitative* method. The names of the schools originate from two separate views on how to study "reality" (Hollis, 1994):

1. The *Explaining* philosophy has its roots in natural science and claims that a single general method can be used to describe reality in all sciences. The

Explaining philosophy originally stated that there is a single reality that will be the same *regardless of human beliefs* (see description of Positive Science in Lipsey, 1963). According to the Positivistic view of science, there exists an objective truth that is independent of the "participating" persons' feelings about this truth. Positive Science can be described as an empirical science. See Figure 2.

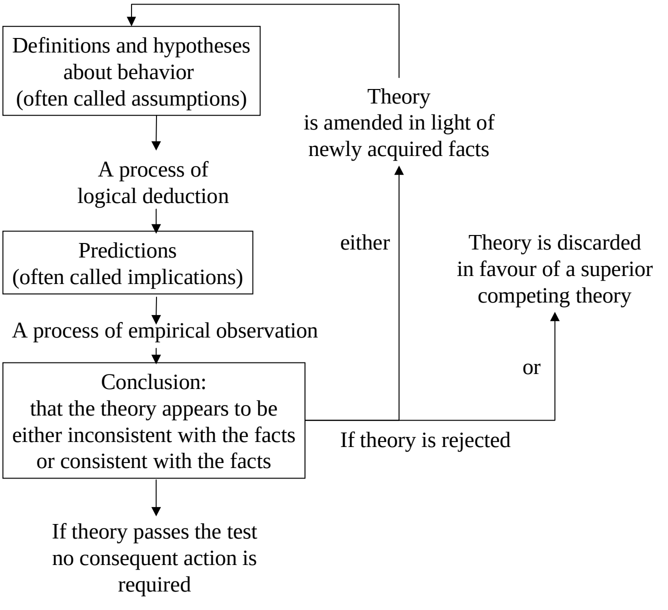


*Figure 2. Positive Science as a method (from Hollis, 1994; Lipsey, 1963).*

More recent findings within the Explaining School in Figure 1 have questioned the Positive view of science. Popper (1969) states that a theory is only scientific if it is testable and refutable. Popper also states that one can only prove that certain theories are false (*falsification*), and that a theory is not proven true even if it is tested successfully one or more times. According to Popper, one should seek to falsify a theory. The theory that is falsified is then improved and tested again. *Pragmatism* (Quine, 1953) claims that the human mind and the researcher's beliefs are important when deciding what should be regarded as knowledge. Also, theories and beliefs can be revised by experience. Theory and experience are interrelated. The theoretical background that affects the presented research is stated in Section 2. Research Paradigms (Kuhn, 1970) further describes how certain theories affect what we believe is true and how they determine what kind of research is performed. When the theories, or paradigms, forming our presumptions are finally revised as science progresses and finds new “truths”, then paradigm shifts occur.

Recent research in the Explaining school, as proposed by Popper’s method of falsification, Quine’s Pragmatism, and Kuhn’s paradigm shifts, poses objections to Positive Science. Still, the use of research questions, hypotheses, and empirical studies remains very extensive. Furthermore, Quine’s Pragmatism and Kuhn’s theory of paradigms shifts have opened up the research philosophy of the Explanation school to the uniqueness of human interpretation and understanding. This aspect is further stressed in the Understanding school of science described below.

2. The Understanding view of the research philosophy of science can be summarized as “*Instead of seeking the causes of behavior, we are to seek the meaning of action. Actions derive their meaning from the shared ideas and rules of social life, and are performed by actors who mean something by them*" (Hollis, 1994, p. 17). The Understanding school aims principally at describing social science, and claims that here the hermeneutic method should be used (i.e. human interaction). The basic assumptions that form the Understanding/qualitative/hermeneutic method are: (1) Human actions have *meaning*, (2) The interpretation of facts differs according to an individual’s set of prejudices and pre-understandings, (3) There is a moral dimension of social science, (4) *“It is not possible to understand a part of something without understanding the whole*” (Månsson and Sköldberg, 1998), and (5) “*Language has meaning…language is often seen as the key to understanding how thought informs action*” (Hollis, 1994, p. 161). By continuously alternating between understanding parts of the problem and trying to understand the picture as a whole, it is possible to increase understanding of the subject and avoid becoming trapped in the hermeneutic circle (see assumption (4) above). The hermeneutic circle is then transferred into a spiral towards better and better understanding of the subject. See Figure 3.

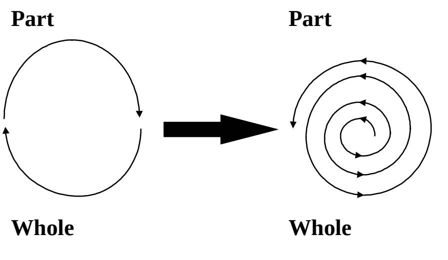


*Figure 3. Hermeneutic circle transferred into a spiral towards better understanding.*

- **A combination of hermeneutic and positive science**

It is the author's belief that when dealing with natural science, the Explanation approach is the best method. However, in product development many technical projects sooner or later interact with human beings. Humans are not as rational as positive science may suggest. Therefore, a method that combines explaining and understanding is often needed in product development.

A research methodology is adopted in this thesis that is based on the Explanation foundation combined with an holistic view (see shaded box in Figure 1), but deals with the human aspects and the interviews of the presented studies in an Understanding and hermeneutic way.

The author has actively taken part of the industrial case studies performed in Papers A and B. Conducting projects as part of a company affects understanding of the subject. Some of the issues in these papers are colored by the thoughts of coworkers and the needs of the companies. It is the author's belief that admitting these risks and seeking to an open-minded approach helps the researcher to be as ”objective” and reliable as possible. It is the intention and belief that the projects and conclusions will provide helpful insight also for other companies and academic institutions besides those included in the original case studies.

Table 1 summarizes the research method used in the appended papers. Certain comments regarding the research methods follow below. The research method for the papers is also described in the appended papers. Comments regarding the methods in the appended papers:

Papers A and B: *Interviews* were open and loosely structured. The interviewer prepared questions but no answer alternatives were presented to the interviewee. Notes were taken during the interviews. The notes were reworked into full text directly after the interviews. The interviewees were sent copies of the printed interview questions and the interpretation of the answers in order to confirm that the interviewer had correctly understood the answers.

The research method for Paper C relies on formal proofs while Paper D is based on mathematical derivation of equations. The PFM method in Paper E is based on an assembly of existing techniques from the statistical multivariate literature as well as the classification field of research.

The survey in Paper F was based on short telephone interviews with prepared questions but no answer alternatives. Paper F presents the questionnaire. Due to the simplicity and shortness of the questionnaire it was decided that copies of the notes from the interviews should not be sent to the respondents. Paper F was sent to the respondents that indicated interest in the presented research.

*Table 1. Appended papers and research methodology.*

| Letter of Paper | Type of Study | Number of applications of suggested approach |
|---|---|---|
| Paper A | Theory development. Interviews Case study to test hypothesis. | 2 |
| Paper B | Theory development. Interviews. Case study to test hypothesis. Computer simulations. | 1 |
| Paper C | Theory development. Mathematical proof. Academic example to simulate practical impact. Computer simulation. | 1 |
| Paper D | Theory development. Mathematical derivation of formula. Academic examples to simulate practical impact. | 2 |
| Paper E | Theory development. Comparison of competing methods. Academic example to simulate practical impact. Computer simulation. | 1 |
| Paper F | Theory development. Comparison of competing methods. Academic example to simulate practical impact. Computer simulation. Short telephone interviews/survey. | 1 |

## 1.6 OUTLINE OF THE THESIS

Section 1.6.1 describes various activities related to product development within a company and how the research presented is aligned with these activities. A short summary of the appended papers is given in Section 1.6.2. Section 2 presents the theoretical basis of this thesis and Section 3 discusses how the research questions and their corresponding hypotheses were approached. Section 3 also discusses certain topics related to the research questions that were omitted from the appended papers owing to limitations on the number of pages in the papers. Section 4 presents plans for future research and Section 5 presents final conclusions.

### 1.6.1 FRAME OF REFERENCE

This section provides an overview of research related to product development and describes how the papers and research questions in the thesis relate to this view of product development.

Product development within a company consists of activities at different levels of scope. See Figure 4. The corporate strategy is dependent on what is performed in daily engineering work, and vice versa. For instance, corporate executives need to have a grasp of daily engineering work in product development in order to understand core competencies of the firm, while engineers need to be familiar with the corporate strategy in order to adapt product development to changing competitive environments. To achieve significant improvements in product development, it is necessary to address every related activity at different levels of scope.

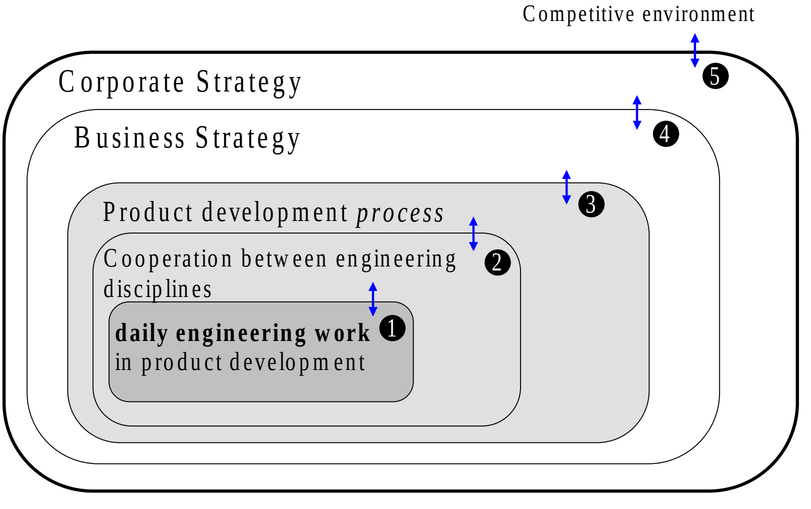


*Figure 4. Product development at different levels of scope.*

Below follows a description of the various aspects of product development as shown in Figure 4, together with references to current research.

1. *Daily engineering work*: Many tools and methods are under development for rationalizing product development work by engineers. Tools such as Computer Aided Design and Computer Aided Manufacturing are continuously being developed, along with new and more powerful computers and computational methods (see for instance Senin et al., 1999). Guidelines for designing and describing a product are also being developed (see Section 2). These may range from new physical principles to new

methods of computing specific problems or general problem solving approaches.

2. *Cooperation between disciplines*: It is widely acknowledged that cooperation improves output in many projects (Bergman and Klefsjö, 1994; Deming, 1986; Robbins, 1994; Sohlenius, 2001). The main objective of this human factors oriented aspect of product development (Fleischer and Liker, 1997) lies in improving and rationalizing co-operation. See also Elg et al. (1998).

3. *Product development process*: Processes describe the tasks that are repeated in many product development projects. These may involve processes for leading product development projects and thereby including the major steps as prescribed by the company. A process may also consist of steps in a dimensional analysis. To improve the quality of product development, it is important to improve the process of product development (Bergman and Klefsjö, 1994; Deming, 1986; Deming, 1994). Companies are often unaware of the actual product development process that exists in their organization. Eppinger et al. (1994) use the Design Structure Matrix for identifying and evaluating these processes. Based on process identification, Carrascosa et al. (1998) continue to explore the possibilities of the Design Structure Matrix tool in order to estimate product development time. Wheelwright and Clark (1992), Clausing (1994), Pahl and Beitz (1996), and Sohlenius et al. (1976) provide examples of suggested "good" processes for product development. Wheelwright & Clark discuss processes from a more management-oriented perspective, whereas Pahl & Beitz are more engineering-oriented. Clausing combines these levels of scope. Sohlenius et al. present an early version of concurrent engineering by their focus on manufacturing, customization and order controlling aspects within product development.

4. *Business Strategies*: A business strategy sets out the preferences for how a specific and relatively autonomous part of the firm called a Strategic Business Unit (SBU) should compete. Other organizational solutions will naturally include other organizational parts than SBUs, but the corporation is probably divided into some sort of units with a set of defined strategies and these strategies will then be related to product development in a similar way to the strategies of SBUs. The business strategies and their business units affect product development indirectly since they are the internal customers of the product development process. Examples of business strategies are: Market Strategy, Technology Strategy, Finance Strategy, Manufacturing Strategy, etc. Business strategies are often managerial in nature and are discussed in the broad field of management and strategy

(Christensen, 1997; Erickson and Shorey, 1992; Ghemawat, 1991; Hax and Majluf, 1996; Kotler, 1997; McGrath, 1995; Porter, 1980; Porter, 1985; Prahalad and Hamel, 1990).

5. *Corporate Strategies* define the ways of achieving the ultimate goals of the corporation. Corporate strategies are very similar to business strategies, but are larger in scope. Since corporate strategies affect business strategies, they also affect product development. Currently, there is a clear trend towards corporate strategies aimed at “maximizing shareholder value” (Boquist et al., 1998), i.e. strategies that seek to increase the shareholder’s Return on Investment through large dividends and steady growth in stock prices. An overview of the different strategic schools of thought is presented in Mintzberg and Lampel (1999).

Figure 4 and the above description stress the fact that product development can be improved at many levels within the company.

The arrows between the different aspects of product development in Figure 4 indicate that coordination and well defined interfaces are needed between the various company activities related to product development (see for instance Hax and Majluf, 1996; Wheelwright and Clark, 1992; and section 3.1). Such coordination enables a speedy product development process and quick responses to changes in the competitive environment. Goals for daily engineering work need not be the same as goals for the company strategy, but coordination avoids contradictory goals, strategies and activities. See Figure 5 and Figure 6. Akao (1991) and Bergman et al. (1993) also discuss the importance of clarifying and coordinating the company’s goals between the organizational units and processes.

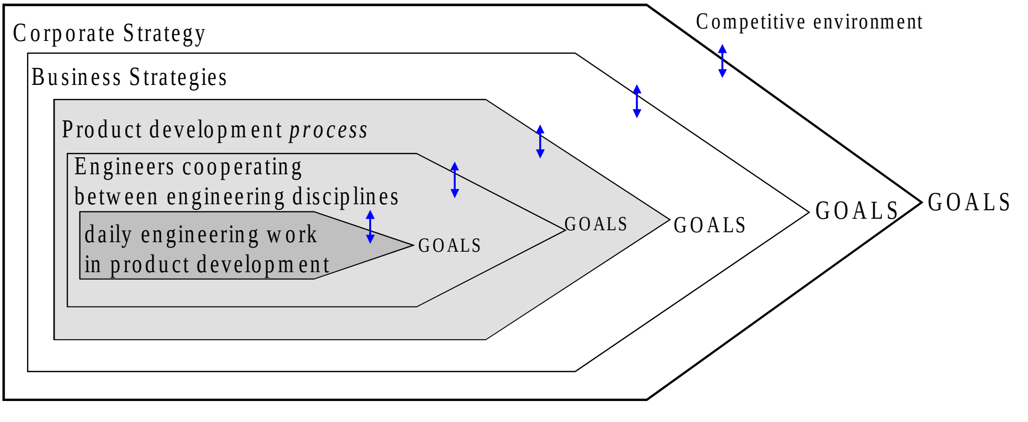


*Figure 5. Increased speed and flexibility in product development through shared goals and well defined process interfaces.*

The research questions and their corresponding research (the papers related to research questions one to six are presented in Appendix A – F) address quality improvements at different levels of product development. The focus is on means of achieving quality improvements through increased product performance related robustness at the level of daily engineering work, although a tool for designing as well as aligning strategies and process plans with activities is also considered. If product development is carried out as indicated in Figure 5, then the product development activities within a company could be described as a ship, in which every aspect of product development is necessary in order to achieve the different goals. See Figure 6. Figure 6 also describes what aspects of product development, mentioned above, are addressed in the research papers.

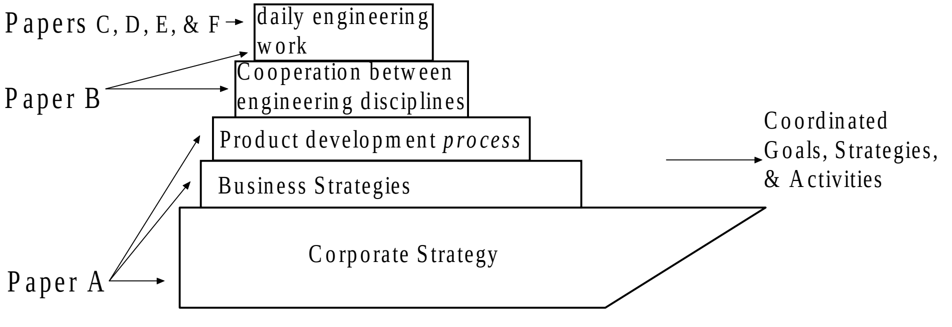


*Figure 6. Product development described as a ship, and the way in which the papers in this thesis provide tools for different levels of scope of product development.*

The field of research that the papers primary address is depicted Figure 7. The Venn diagram in Figure 7 also stresses how the studied fields of research often overlap.

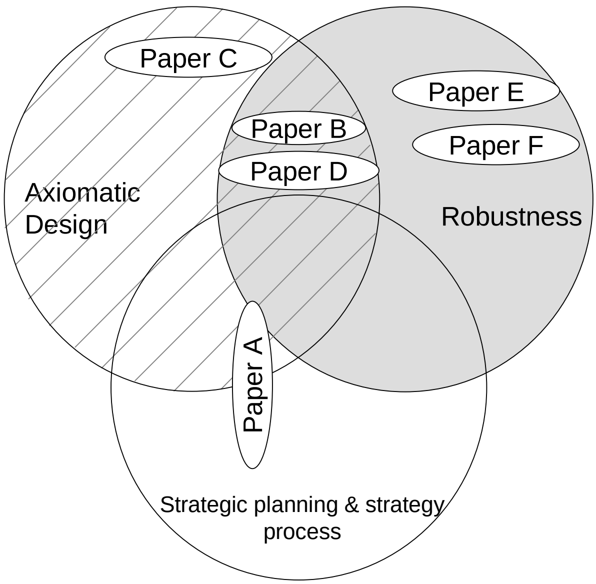


*Figure 7. How the contents of the papers relate displayed in a Venn diagram.*

### 1.6.2 SUMMARY OF APPENDED PAPERS AND AUTHORS' CONTRIBUTION

**Paper A:**
**Strategic Planning based on Axiomatic Design**

A method for designing strategies is developed. A mapping of company goals and the chosen strategies for fulfilling these goals is used to design a strategy. Activities for executing the strategies are also defined. The mapping process is based on the engineering design method Axiomatic Design. Examples of the way in which Axiomatic Design could be interpreted in the non-engineering field are given.

With the exception of Section 4.1 ”Designing a business plan”, the paper was written by Engelhardt. Section 4.1, together with ideas and comments, was written by Nordlund.

**Paper B:**
**Improving Products and Systems by combining Axiomatic Design, Quality Control Tools and Designed Experiments**

The paper describes how to utilize engineering design theory and designed experiments in order to capture as much *a priori* engineering knowledge as possible when seeking to improve product performance. The presented approach has problem solving as its objective. It stresses the importance of tackling the problem with a systematic approach all the way from the beginning of problem formulation until the improvement efforts are implemented. It is found that a combination of product modeling by the engineering design method Axiomatic Design and designed experiments overcomes weaknesses of the methods.

The paper was written by Engelhardt.

**Paper C:**
**Computing the Information Content of Decoupled Designs**
This paper presents an alternative approach to computing the Information content in decoupled designs. In the framework of the engineering design method, Axiomatic Design, the Information content can be used to select the preferred design solution from a set of suggested solutions. It is shown that the presented method of computing Information content for decoupled design concepts is more accurate than summing the Information content of the design parameters in the design. Using the presented computational method can lead to selection of design concepts with a higher probability of success, compared to the currently often used method of summing information content for decoupled designs.

The paper was written by Prof. Frey. The math (i.e. the computational solutions) was developed by Prof. Frey. Ebad Jahangir helped fine-tune some equations and contributed suggestions and comments. The problem was identified jointly by Prof. Frey and Engelhardt, and a solution approach was discussed. The related work section (Section 3), together with suggestions and comments, was also contributed by Engelhardt.

**Paper D:**

**Computing the Economic Value of Robustness with the Axiomatic Design Framework**

An equation for computing the economic value of robustness in terms of quality loss due to variation in design parameters is derived. The formula combines the information stored in Axiomatic Design's design matrix with Taguchi's quality loss concept. It thereby forms an engineering metric for evaluating design concepts that readily can be combined with other business oriented measures such as Net Present Value and investment cost estimates. Also, the equation provides a relationship between the form of the design matrix and the economic value of robustness. This relationship shows, contrary to our expectations, that the economic value of robustness *cannot* be predicted by the degree of coupling in the Design Matrix, i.e. uncoupled/decoupled/coupled.

Engelhardt identified the research opportunity and formalized the initial paper idea. The research was carried out in close cooperation between Engelhardt and Lee. Equation (10) in the paper was derived separately by both researchers. The paper was written jointly by Engelhardt and Lee. Prof. Frey suggested the manufacturing machine concept as a clarifying example. He also contributed suggestions and comments along the way.

**Paper E**

**Robust Manufacturing Inspection and Classification with Machine Vision**

A method for selecting a subset of product features that enables a robust classification with machine vision is assembled. The classification is based on the Mahalanobis Classifier and signal-to-noise ratios. The feature selection method is based on a principal component transformation of the data set and a multimodal overlap measure and is abbreviated (PFM). PFM compares favorably to Taguchi's approach to multivariate robustness (Mahalanobis Taguchi System, MTS) applied to the same simulated manufacturing problem.

Engelhardt and Häcker wrote this paper. The theoretical work of the paper was carried out jointly by Häcker, Engelhardt, and Frey. Häcker did most of the Matlab programming. The coding was often carried out as Pair Programming (Williams et al., 2000) with Häcker typing and Häcker and Engelhardt simultaneously attacking the problem in front of the same computer. Findings and solution approaches were continuously discussed with Prof. Frey. The paper is a continuation of an initial research effort carried out by Frey (1999).

**Paper F**

**The Role of the one-factor-at-a-time Strategy in Robustness Improvement**

The one-at-a-time strategy for changing factors in designed experiments is compared with the orthogonal arrays in the Taguchi Method. It is found that the one-at-a-time strategy for improved robustness is preferable to orthogonal arrays in many experimental situations with low experimental error.

Engelhardt wrote this paper. Engelhardt performed the Matlab coding and identified the Wheatstone Bridge example. Engelhardt and Frey initiated and planned the project jointly. Frey and Engelhardt analyzed the results and arrived at the conclusions together. The research, and its progress, was continuously scrutinized at the weekly Robust Engine Group meetings at MIT's Dep. of Aeronautics and Astronautics. Many good ideas and suggestions were made by professors Darmofal, Greitzer, and Weitz as well as by fellow graduate students Vince Sidwell, Victor Garzón and Beilene Hao.

# 2 THEORETICAL BASIS

## 2.1 ENGINEERING DESIGN

What is engineering design? The dictionary describes the *noun* “design” as: (1) A plan or sketch for making a building, machine, garment, etc., (2) Lines or shapes forming a pattern or decoration, (3) A plan, purpose, or intention; whereas the *verb* design is to *produce* a design for something (Abate, 1997). Synonyms for the verb design are: plan, invent, create, devise, sketch out, develop, organize, or frame. Two definitions of design from an engineering perspective are: (1) “To conceive the idea for some artifact [i.e. man-made object] or system and/or to express the idea in an embodiable form” (Roozenburg and Eekels, 1995), (2) “Design involves a continuous interplay between *what we want to achieve* and *how we want to achieve it*” (Suh, 1990). The later statement, (2), clarifies how the “expressing” of the idea in an embodiable form in (1) takes place.

Engineering design focuses on *how* to design in an engineering context. Engineering design methods can be classified into two categories (Konda et al., 1992; for a similar classification see Stake, 1999):

1. Focus on *process models*. Process models can be either *descriptive* or *prescriptive*. *Descriptive* process models describe sequences of design activities common in design. For examples of descriptive design models, see Cross (1989). *Prescriptive* process models prescribe a preferred sequence of design activities that will lead to better design. For examples of prescriptive engineering design models, see Sohlenius et al. (1976), Pugh (1991), Hubka and Eder (1992), Clausing (1994), Ulrich and Eppinger (1995), and Pahl and Beitz (1996).
2. Focus on *artifact models*, which stress the result of the design process, i.e. the product. Artifact models may be either prescriptive, such as Axiomatic Design (Suh, 1990), or descriptive, such as the chromosome model in the theory of domains (Andreasen, 1992). TRIZ is another prescriptive engineering design method that focuses more on creativity and specific topics of problem solving (Altshuller, 1988).

The engineering design method that was used in Papers A, B, C, and D presented in this thesis was Axiomatic Design. The method is introduced below, together with the reasons for choosing it as the theoretical basis for the engineering design aspects of the research.

### 2.1.1 AXIOMATIC DESIGN

Axiomatic Design (Suh, 1990; for early versions see Suh et al., 1978a; Suh et al., 1978b; Suh et al., 1979) has been chosen as the theoretical basis of engineering design in this thesis. This is due to the fact that Axiomatic Design especially addresses the internal relationships of a design and applies a probabilistic view of design.

Axiomatic Design is a principle-based design method where the product is modeled in four domains: (1) The customer domain, (2) The functional domain, (3) The physical domain, and (4) The process domain. See Figure 8.

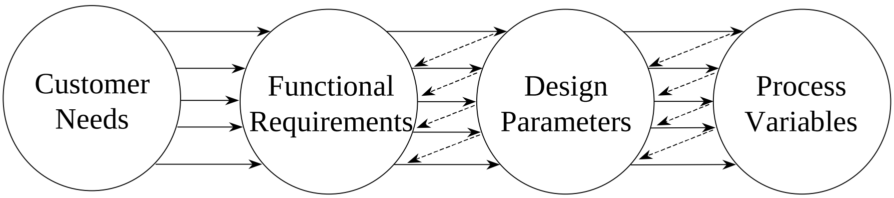


*Figure 8. Design domains in Axiomatic Design.*

Designing with Axiomatic Design includes a mapping process between customer needs (CNs), functional requirements (FRs), design parameters (DPs), and process variables (PVs). This mapping assures that there are means in one domain of fulfilling the objectives stated in another domain.

The mapping is often performed between functional requirements (FRs) and design parameters (DPs), but should in concurrent engineering also be performed between design parameters (DPs) and process variables (PVs). This mapping process can be displayed as in Figure 8, and is represented by the design equation (1) for describing the relationship between the functional and physical domain. The relationship matrix (i.e. Design Matrix, or **DM**) in equation (1) describes how certain design parameters affect the functional requirements. See equation (2). A Design Matrix can also be set up to describe the relationship between design parameters and process variables, or between functional requirements and process variables.

$$\{\mathbf{FR}\} = [\mathbf{DM}]\{\mathbf{DP}\} \qquad (1)$$

where

$$\mathrm{DM}_{\mathrm{ij}} = \frac{\partial FR_i}{\partial DP_j} \qquad (2)$$

The choice of high-level design concept determines how the decomposition of the functional requirements, design parameters, and process variables is performed in order to achieve a more detailed product description at a lower level. This procedure is called zigzagging.

Axiomatic design theory provides guidelines (consisting of axioms, theorems, and corollaries) about the relations that should exist between the different domains. These guidelines answer the question: will a set of design parameters (DPs) satisfy the functional requirements (FRs) in an acceptable manner? This reasoning should also hold between DPs and PVs. The relations between customer needs and FRs, however, are more loosely structured. The guidelines are based on two design axioms:

Axiom 1: The independence axiom (Maintain the independence of functional requirements)

Axiom 2: The information axiom (Minimize the Information content, i.e. maximize the probability of success)

The design can be graphically expressed with an FR-DP tree, or a function-means tree (see Andreasen, 1980; or a similar approach in Marples, 1961). A more detailed introduction to Axiomatic Design can be found in Nordlund (1996). Magrab (1997) presents a product development process where cross-functional teams, Axiomatic Design, designed experiments and various Design-For-x are integrated.

## 2.2 ROBUST DESIGN METHODOLOGY

The goal of robust design is to develop designs that are insensitive to disturbances and perform well under a wide range of conditions. Design (a) in Figure 9 is more robust than design (b). The variance of (a) is less than the variance of (b).

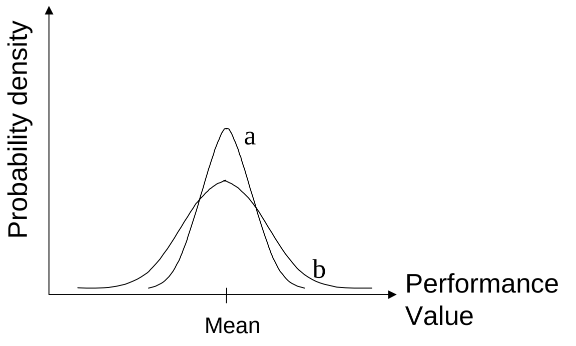


*Figure 9. Robust products have smaller performance deviations.*

A robust design ensures lower quality-costs than non-robust products. Assume two competing design concepts, (a) and (b), that are to be evaluated. See Figure 10. Product (a) has on average a smaller deviation in performance than product (b). On the other hand, product b’s performance is always within the specified performance tolerances (Target ±t). The almost uniform probability distribution of (b) is common when manufacturing inspection eliminates the products that are outside the tolerance limits. The quadratic quality loss function is the reason why the more robust product (a) is preferred to product (b) even though product (a) on rare occasions performs outside the tolerance limits. The quadratic quality loss function describes the cost that a product entails for the company, even though its performance value is within specified tolerances (Taguchi, 1979; Taguchi, 1981; Taguchi, 1993). Let’s take trucks with a Drift/Pull problem for example. Trucks with a Drift/Pull problem drift excessively to either the right or the left when the steering wheel is released. See also Engelhardt and Meiling (1997), Section 3.2, or Paper B. Drift/Pull causes some customers complain and make warranty claims when the truck performs just outside the tolerance limits, whereas others complain when the truck performs just within the tolerance limits. Hardly any customers complain when the truck performs at target value, which is zero Drift/Pull at the specified speed.

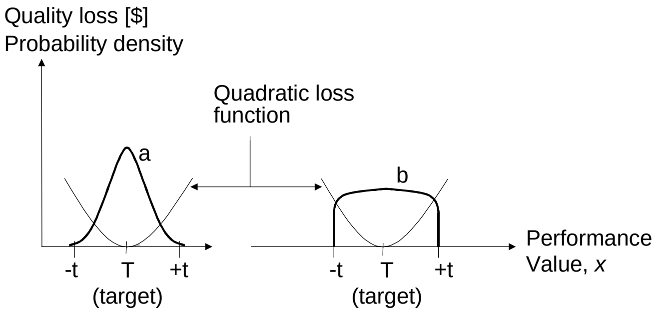


*Figure 10. Robust products lead to lower quality costs due to the quadratic quality loss function.*

The quality cost of a design concept can be described as in equation (3) and equation (4), if the quadratic loss function is assumed. The quadratic loss function contributes to increasing quality cost levels as a quadratic function of performance target deviation. See Figure 10. The monetary loss due to target deviations and lack of robustness is called *quality loss*, *L(x)*, and is obtained by multiplying the performance distribution of the design concept by the quadratic loss function and integrating over all possible performance values:

$$L(x) = \int_{-\infty}^{+\infty} k\left((T - x)^2\right) p(x)\, dx \tag{3}$$

where

$T$ = target performance value
$x$ = performance value
$k$ = quality loss coefficient (a constant).
$p(x)$ = the probability density function for $x$.

The quality cost is assumed to be zero if $\bar{x} = T$ . The quality loss cost can also be described as follows (for a summary of the quadratic loss function see Hynén, 1994;  or Phadke, 1989):

$$L(x) = k\left[(T - \bar{x})^2 + \sigma_x^2\right] \tag{4}$$

where

$\bar{x}$ = mean performance value
$\sigma_x^2$ = performance variance.

The quality loss coefficient, *k*, is a constant often used for determining economically optimal tolerance limits for a design. For details of the calculation of *k*, see Clausing (1994), Hynén (1994) or Phadke (1989). One way of calculating *k* is to start with a known value of a quality loss cost, *L(x)*, for a given performance deviation from target. Quality loss costs for tolerance limits in manufacturing could be used since they can sometimes be computed. Another approach is to estimate quality loss costs for so called *functional limits* (i.e. the value of *x*, when half the products would fail in their applications). *k* is then found by using the approximation of the quadratic, or parabolic, function describing *L(x)* at a specific target deviation as $L_{level}(x) = kx^2$, and then solving for *k*. Consequently,

$$k = L_{level}(x_i) \big/ x_i^2 \tag{5}$$

where $x_i$ is the known value of *x* that leads to a specific quality loss cost.

Returning to the question of whether concept (a) or (b) in Figure 10 is to be preferred, equation (4) shows the quality loss to consist of two components:

1. $k(T - \bar{x})^2$, describing the quality loss due to deviations from target
2. $k\sigma_x^2$, describing the quality loss cost to deviations of *x* around its own mean.

If both design (a) and design (b), discussed above, have equal mean values (E($X_a$)=E($X_b$), or $\bar{x}_a = \bar{x}_b$) and the mean values are set to target ($\bar{x}_a = \bar{x}_b = T$), then the bias term in equation (4) can be ignored. Since $\bar{x}_a = \bar{x}_b = T$ for concept (a) and (b), the only component that distinguishes concept (a) from (b) is the performance variance. Concept (a) in Figure 10 has a smaller variation around its mean than concept (b) and is therefore superior to concept (b). The more robust design concept (a), in Figure 10 is the better alternative.

Clausing (1994), Phadke (1989), and Deming (1994) discuss similar examples of quadratic quality loss functions. The conclusion is that variance minimization in product performance is an important aspect of high quality products. The goal of variance minimization also stresses the importance of continuous improvements.

A common approach among all versions of robust design is to: (1) understand and classify the noise factors (i.e. disturbances, different operating conditions, etc.), (2) expose the design to the noise factors, (3) minimize the product's variance, and (4) set the mean to target.

The use of *designed experiments* is an effective way of minimizing variance by tackling steps 2 - 4 in the list above. Designed experiments reduce the experimental effort needed for finding the combination of controllable factor-settings of a design that minimize performance variance, given the existing noise factors. An experiment with eight unknowns, at two levels each, produces $2^8 = 256$ experimental combinations if the experiment is carried out changing one factor at a time. A fractional factorial design, such as a $2_{IV}^{8-3}$ [1] designed experiment, reduces the experimental effort from 256 to 32 experiments. Further discussions on fractional factorial designs, as well as introductions to Design of Experiments (DoE), are presented in Box et al. (1978), Bergman (1992), O´Connor (1995), and Magrab (1997).

There are two major schools with regard to the method of performing designed experiments for achieving robust design:

1. Taguchi’s method to robust design (Clausing, 1994; Phadke, 1989; Taguchi, 1987). The Taguchi Method focuses on speed and reduction of experimental effort. It advocates highly saturated experimental designs in which many design parameters are examined in a limited number of experiments. Optimization is performed according to a metric that seeks to combine target deviations and size of variance (a signal-to-noise ratio).

2. A classical statistical approach to designed experiments that can also be used to achieve robust designs, is Response Surface Methods (RSM, see Box and Draper, 1987; Myers and Montgomery, 1995). See also Hynén (1996). The Response Surface Method focuses on prediction accuracy. The Response Surface Method can be used to achieve robustness by combining classical Design of Experiments techniques with evaluation of the noise factors’ effect on the response and a focus on variance minimization. RSM stresses separate evaluation of mean response and variance response.

Simpson et al. (1997) provide a comprehensive overview and description of the advantages and disadvantages of the various ways of using statistics in design. They also discuss special circumstances when using statistical experiments in computer simulations.

Each development situation has its own context and limitations. The author’s opinion regarding choice of experimental design is that the context of the situation must determine the most suitable approach. The RSM approach is not always superior to the Taguchi Method, or vice versa. The knowledge and preferences of the design team’s statistical or experimental leader may be the most important aspect. However, it is important to remember that the goal of the experiment is to improve product robustness and product quality.

An interesting example of an analytical and *non*-experimental approach for robust design in early phases of product development is presented in Andersson (1996).

[1] Standard notation for fractional factorial designs (see Box et al., 1978).

# 3 ROBUST PRODUCT DEVELOPMENT

This section describes a number of tools and methods for robust product development. Section 3.1 starts on a high strategic level by presenting a tool for designing and company-customizing product development strategies and processes. The tool also seeks to align the designed strategy with the overall business and corporate strategies of the company. Section 3.2 presents an approach to robust quality improvements through the development of existing products. Section 3.3 describes a method for calculating the probability of success in decoupled designs. How to compute the economic value of robustness due to variations in the design parameters is described in section 3.4. Section 3.5 presents and compares two methods for multivariate robustness in terms of classification in the presence of noise. More specifically, the methods aim at selecting the optimum number of features to base the classification upon, so that the classification will be robust. The orthogonal arrays in the Taguchi Method are compared to the one-factor-at-a-time experimental strategy in section 3.6. A qualitative and comparative table that compares three experimental methods and their applicability in different experimental conditions is also presented.

The tools and methods presented in this section could be used to address specific questions as part of a larger effort to create a robust product development process (see for instance Clausing, 1994).

## 3.1 A TOOL FOR STRATEGIC PRODUCT DEVELOPMENT

There is a need to align Product Development with overall company strategies since company strategies set up preferences that guide the firm and its product development efforts. See Figure 4 and Figure 5. Figure 11 describes how this section, and its corresponding Paper A, relates to the different levels of scope for product development described in Section 1.6.1 “Frame of reference”. It also depicts the fields of research for Paper A.

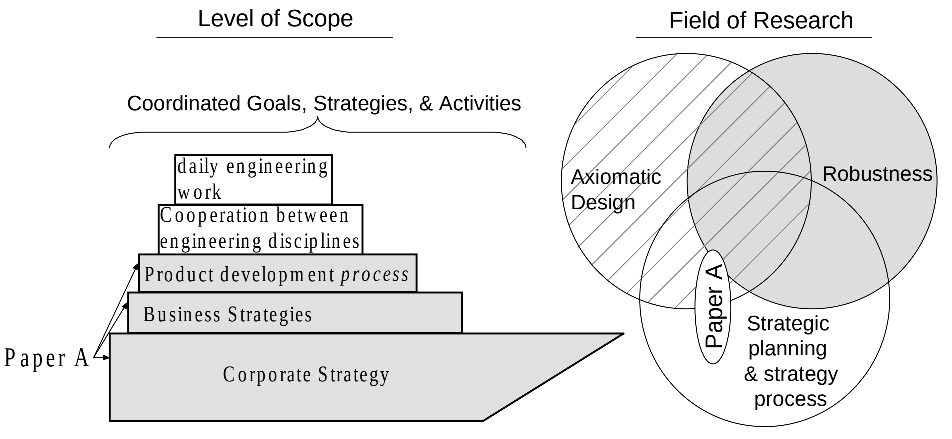


*Figure 11. How this section and its corresponding Paper A relate to different levels of scope for product development and the field of research.*

A strategy improves the competitive advantage of the company (see for instance Ghemawat, 1991; Hax and Majluf, 1996; McGrath, 1995; McGrath, 1996). The strategy has to be consistent all the way from high-level company goals and visions down to the actual tasks carried out by the employees. The strategy also has to be customized for each company. The company's organization, culture, and area of business satisfy company-unique needs. Such needs have to be taken into account when *designing* a strategy. The strategy may relate to product development, technology, competence, business, corporate strategy, etc.

Tools are needed that improve both designing of the strategic content, and the strategy process. This arises from three strategy-related problems that are common and important to address: (1) too many strategies lack action plans to fulfill their high-level goals (Nordlund, 1996), which makes these strategies diffuse and difficult to realize; (2) there are very few tools for customizing and designing a strategy into a company-specific and detailed level; (3) strategy related processes are seldom analyzed and iterative loops between organizational units can often continue for a very long time without bringing the projects closer to their goals.

Based on the needs identified above, this section investigates research question 1: *Can the engineering design theory of Axiomatic Design, if used to help design a company strategy, also help design the corresponding strategic process?*

Earlier findings show support for the usability of Axiomatic Design in non-engineering situations (Nordlund, 1996) and lead to the hypotheses:

*Hypothesis 1.1*: Axiomatic Design *cannot*, if used to help design a company strategy, also help design the corresponding strategic process.

*Hypothesis 1.2*: Axiomatic Design can, if used to help design a company strategy, also help design the corresponding strategic process.

The author had the opportunity to test these hypotheses in a case study. See Paper A and Engelhardt (1998). The case study involved the development of a technology strategy for a large industrial company. The author participated actively in the development project. Axiomatic Design was used as a tool for designing the strategy as well as the implementation process for the strategy.

For this purpose, the terminology in Axiomatic Design was renamed in order to increase acceptance for the Axiomatic Design framework within the strategic planning community. Based on Nordlund (1996), functional requirements were translated into Goals, design parameters into Strategies, and process variables into Activities. See Figure 12.

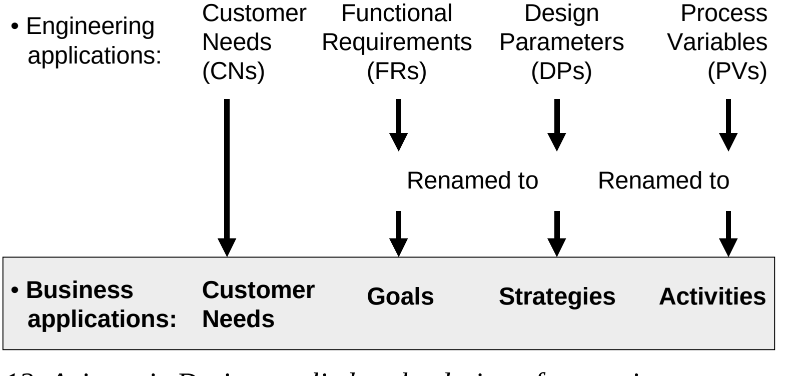


*Figure 12. Axiomatic Design applied to the design of strategies.*

The design process for the strategy was similar to the design process in engineering design. See Figure 13.

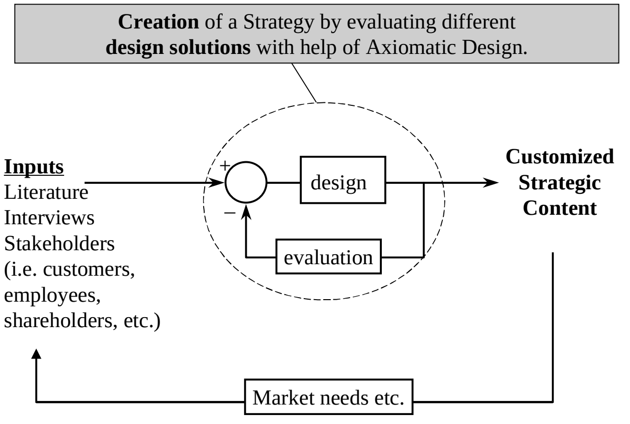


*Figure 13. The design process (based on Suh, 1990).*

The following were some of the findings from the case study:

A leader-follower approach (see Chen and Lewis, 1999) adopted for the first and second axiom in Axiomatic Design was found valuable and useful when alternatives to coupled design solutions were very hard to find. In terms of processes, it was important to recognize that interaction between departments is part of a learning organization, and should therefore not be completely designed away. However, couplings between organizational entities often yield iterative loops that reduce the probability of success and increase the time required to implement the strategy. It was therefore important to understand these iterations and to be able to control them. In these cases of coupled organizations, a leader-follower approach where *decoupling of the design is achieved by deciding on a preferred workflow*, was found valuable. The axioms in Axiomatic Design have to be interpreted with some caution when working with design of non-engineering products.

It is the authors' belief that the design axioms should, so far, be considered strong design principles instead of axioms when designing non-engineering products. Additional research is needed before the design axioms can be called axioms even outside the engineering domain.

The use of Axiomatic Design for strategic planning was found to provide tight couplings between company goals, strategies, and activities. The experience from the case study was that Axiomatic Design helped the strategic designer to structure and visualize the work and the internal relationships between the goals, strategies, and activities.

Overview and communication were also improved when using a framework such as Axiomatic Design for designing a company-specific strategy. Discussions regarding interrelations and the optimal process for implementation were improved with the help of the design equations.

The idea in Axiomatic Design, i.e. to record Goals (FRs), Strategies (DPs), Activities (PVs), and their interrelationships (Design Matrices), was found valuable to implement as part of corporate memory.

*Conclusions*: Hypothesis 1.1 is rejected, since Axiomatic Design was successfully used in the case study as a tool for designing strategies and strategy processes.

Hypothesis 1.2 cannot be proven, but the successful use of Axiomatic Design in the case study makes hypothesis 1.2 more likely. Hypothesis 1.2 states "Axiomatic Design can, if used to help design a company strategy, also help design the corresponding strategic process".

It is hoped that the approach described in hypothesis 1.2, and above, will be questioned, revised and further improved in future research and practical work.

- **Related research topics**

In the course of the research, parallels between Axiomatic Design and the process evaluation tool Design Structure Matrix (DSM, see for instance Eppinger et al., 1994; Steward, 1981) were identified. Below follows a comparison between Axiomatic Design and DSM.

Design Structure Matrix is a matrix-based tool for product and process evaluation. It focuses on the way in which certain elements in the design process are interrelated. It also suggests new ways of organizing the development process in order to minimize iterations and thereby shorten lead times, etc.

Fundamental differences between Axiomatic Design and DSM exist, although they are both matrix-based and can be used for similar tasks. Below follows a summary of these differences:

1. Axiomatic Design focuses on the relationships, i.e. couplings, between *what* you want to achieve and *how* you choose to achieve it. A Goals-Strategy matrix (or an FR-DP Design Matrix in engineering language) often illustrates this. The Design Structure Matrix checks the relationships among parameters in *what is already designed*, in the product/process (i.e. Strategy-Strategy or DP-DP matrix).
2. Axiomatic Design describes the products in terms of Goal-Strategy trees, FR-DP trees, or similar function-means trees. The Design Matrices are set up for the different levels in the tree hierarchy describing the product. This yields several design matrices for a product when using Axiomatic Design, compared to a single large Design Structure Matrix when describing the product with the DSM approach. The DSM approach presents a better overview of the whole design process compared to the various Design Matrices in Axiomatic Design. The tools for organizational process analysis are less developed in Axiomatic Design compared to DSM.
3. Axiomatic Design includes axioms, corollaries and theorems that provide support on how to achieve, for instance, uncoupled design solutions when designing. These tools are not present when working with DSM. Axiomatic Design is prescriptive and DSM is descriptive.
4. The Design Structure Matrix approach does not claim that couplings between tasks or functions are always bad, but states that in order to increase efficiency these couplings must be analyzed and dealt with in a proper way. Axiomatic Design states that one should always seek an uncoupled design or process solution. Due to the highly coupled nature of human-to-human interaction, the author considers that the *axioms* of Axiomatic Design are better suited to product design than to the design of non-engineering products and processes. Nevertheless, the *method* of Axiomatic Design could be very effective when it comes to designing a product development process. I.e. a product development *process* developed with axiomatic design can turn out to be coupled and still be an efficient process when analyzed with DSM, for instance. Also a process designed with Axiomatic Design often yields a less coupled process than one developed without Axiomatic Design.
5. Axiomatic Design is primarily a design tool and a design analysis tool. DSM is primary a process/task analysis tool.

By observing the differences between Axiomatic Design and the DSM approach stated above, the following conclusion is reached [A parametric and product design oriented version of DSM (Pimmler and Eppinger, 1994) and its relationship with Axiomatic Design is discussed in Paper B, section 5]:

It is a good idea to use Axiomatic Design to design the strategy and thereby achieve a firm relationship between Goals, Strategies and Activities. The use of Axiomatic Design also promotes a solution that is as uncoupled as possible, requiring less time and resources to be completed than a coupled one. The DSM approach is beneficial when it comes to evaluating existing, or proposed, processes. It delivers a clear overview of the relationships between different tasks that have to be performed, and has well developed tools for optimization of its matrix (see for instance Browning, 1996; Cronemyr et al., 1999; Isaksson et al., 1998).

A combination of Axiomatic Design and the Design Structure Matrix approach in process development would probably be beneficial.

## 3.2 COMBINING TOOLS FOR PERFORMANCE RELATED QUALITY IMPROVEMENTS

This section aims at contributing to improved performance-related product quality by combining a design analysis performed through Axiomatic Design with Quality Control tools and designed experiments. Figure 14 outlines the fields of research for Paper B and describes how the research presented in this section relates to different levels of scope for product development.

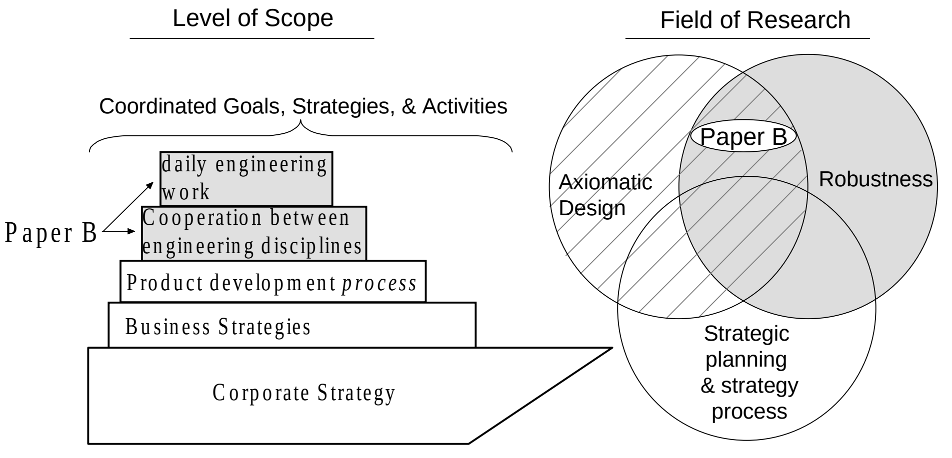


*Figure 14. How this section and its corresponding Paper B relate to different levels of scope for product development and the field of research.*

Numerous design problems are difficult to solve due to the fact that many parameters may contribute to the problem. The internal relationships among these parameters are seldom fully understood. Such design problems could, for instance, concern automobile suspensions and their manufacture, offset screen-printing, or aircraft dynamics. Engineers experience difficulties in determining which parameters to focus on and how changes in certain parameters affect the product or system performance. *How* to make design changes in complex products, where a small engineering change order affects many other parts of the product, is also an important question that has to be addressed.

Engineering design schools provide means for analyzing and understanding the product design. They often rely on subjective engineering judgments when modeling the product structure and product behavior. When quality problems occur in large and complex products, common sense and engineering knowledge may not suffice to solve the problems. There is a need to acquire *new* knowledge about what parameters contribute to the functional performance of the product, and how these interrelate.

The designed experiment can provide new knowledge regarding product behavior and effects from various components on performance. However, a designed experiment is dependent on the quality of the experimental input (i.e. the factors in the experiments) to yield good results.

A combination of product modeling by engineering design tools and designed experiments overcomes the weaknesses of the methods. Engineering design modeling of the product provides good input to the designed experiment, and the designed experiment corrects or improves the assumptions made in the product description phase. The benefit of combining engineering design and designed experiments becomes even clearer when it comes to *evaluating* the results from the designed experiment and *preventing* the problem.

It is the author's belief that such a combined approach with problem solving in focus will provide a faster solution to large and complex quality issues in industry.

Based on the identified needs and possible solutions outlined above, the research question and hypotheses addressed in this section are:

Research question 2: *Is it possible to combine Engineering Design and Quality Control tools with designed experiments in order to utilize a priori knowledge when dealing with problem solving in product development?*

The corresponding hypotheses are:

*Hypothesis 2.1*: Axiomatic Design *cannot* be combined with the seven Quality Control tools and Designed Experiments to form a systematic approach to quality improvements in design.

*Hypothesis 2.2*: Axiomatic Design can be combined with the seven Quality Control tools and Designed Experiments to form a systematic approach to quality improvements in design.

A case study was performed where the hypotheses were tested. See Paper B. The author took an active part in the case study. The study addressed Drift/Pull issues for a truck model at a large automotive company.

Drift/Pull occurs when a vehicle is drifting or pulling either to the left or the right while driving. A Drift/Pull *problem* is said to exist if a driver takes his hands off the steering wheel at 85 km/h and the vehicle changes lane in less than 10 seconds. Warranty claims due to Drift/Pull in the automotive company's light truck entailed significant costs. The Drift/Pull problem was a non-trivial problem that continued for 18 years.

An approach based on hypothesis 2.2 was developed and is described in Figure 15. The approach presented in Figure 15 was carried out at the automotive company's manufacturing plant, the design department, and vehicle dynamics department.

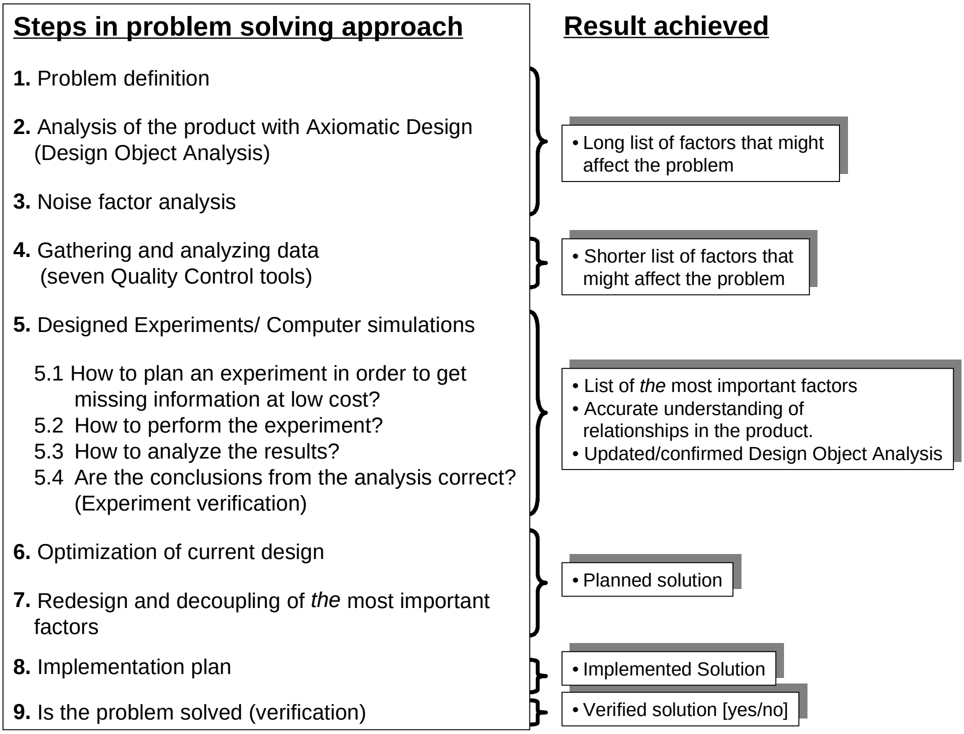


*Figure 15. Approach in solving design problems by combining Axiomatic Design, Quality Control tools and designed experiments.*

The following were some of the findings from the case study:

1. The Drift/Pull problem was found to be a manufacturing plant related problem caused by a combination of lack of robustness in four parameters: (1) caster split; (2) tires in terms of a) Residual Self-Aligning Torque (RSAT), at zero degree slip angle b) Residual Conicity Lateral Force (CRF), at zero degree slip angle; (3) axle parallelism; (4) front weight (center of gravity) bias.

2. Implementing the findings from the case study reduced the Drift/Pull problem. Later, the findings from the case study were also verified for some of the automotive company's other truck models with similar suspension systems.

3. It is the author’s belief that following the presented approach, was the main reason the Drift/Pull problem could be successfully addressed.

4. The approach to quality improvements presented in Figure 15 is a relatively speedy process. The case study was executed during an intensive three-month period, without any specialist knowledge about the Drift/Pull issue at the start of the project.

5. The product analysis in terms of Design Object Analysis (step 2 in Figure 15) is strengthened by knowledge gained from the designed experiment, or computer simulation (step 5 in Figure 15). The designed experiment, on the other hand, is strengthened by the domain-specific product knowledge gathered in the Design Object Analysis, which increases the probability of selecting active factors for the experiment. The two major components of the approach complement each other.

6. Compared to other approaches to quality improvements that also promote the use of designed experiments, the approach presented in this thesis focus more on utilizing engineering knowledge in order to select the active factors for the experiment. The presented approach also puts more emphasis on, and provides means for, problem solving once the root causes of the problem are identified. This is done by utilizing the axioms, corollaries, and theorems in Axiomatic Design in combination with the completed Design Object Analysis when redesigning the product’s factors, or process steps, that affect the quality problem the most.

*Conclusions*: Hypothesis 2.1 is rejected since Axiomatic Design was successfully combined, in the case study, with the seven Quality Control tools and Designed Experiments to form a systematic approach to quality improvements in design.

Hypothesis 2.2 cannot be proven by a single case study, although the case study’s successful use of the approach presented in Figure 15 makes hypothesis 2.2 more likely to be true than before. Hypothesis 2.2 states “Axiomatic Design can be combined with the seven Quality Control tools and Designed Experiments to form a systematic approach to quality improvements in design”.

It is hoped that the approach described in hypothesis 2.2 and in Figure 15 will be questioned, revised and further improved in future research and practical work.

- **Research related to Paper B[2]**

Fundamental differences between *coupling* in Axiomatic Design and *interaction* in designed experiments are addressed in this section. An extended version of equation (1) is presented that allows for capturing of curvature and non-linearity with the notation of Axiomatic Design.

*Interactions*, or *interaction effects*, are sometimes present in designed experiments. For example, if variables *A* and *C* interact, this means that a change in *A* from its low to its high value, for instance, will change the response variable, *y*, differently depending on the *C* value. The graphs in Figure 16 exemplify this. In this case Myers and Montgomery (1995) report that an increase in Gap, *A*, effects Etch rate, *y*, positively when the Power, *C*, is at its low value whereas an increase in Gap decreases Etch rate when Power is at its high level.

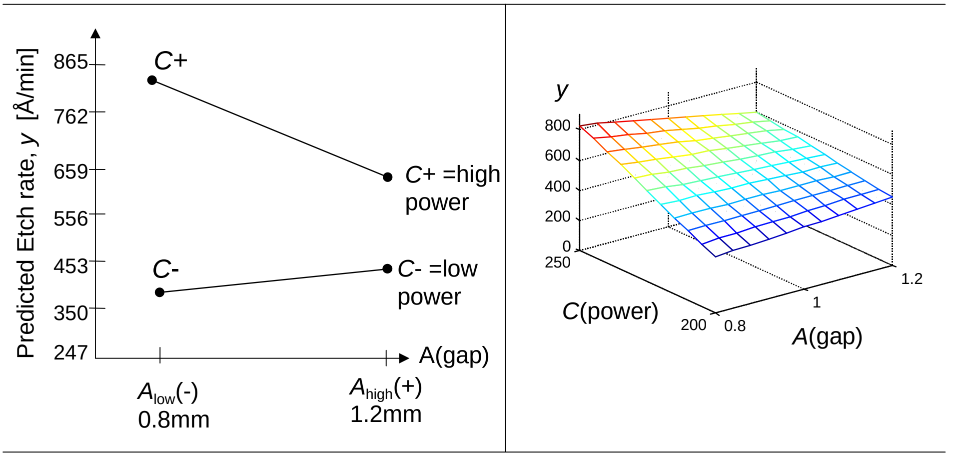


*Figure 16. Interaction effects (adapted from Myers and Montgomery, 1995).*

The lines parallel with the *A*-axis in the response surface in Figure 16 show how the effect on Etch rate, *y*, due to changes in *A* gradually change with increased/decreased *C* values. The regression model that predicts Etch rate in this case is

$$\hat{y} = 563.438 - 37.563A + 153.813C - 76.938AC \qquad (6)$$

[2] I would like to thank Prof. Clausing at MIT for pointing out the need for examining the relationship between Axiomatic Design's coupling concept and interaction effects from designed experiments.

where the *AC* term, or *A* times *C*, describes the interaction effect. The *AC* term allows for modeling how a change in *A* effects Etch rate, *y*, differently depending on the value of *C*.

*Coupling* in Axiomatic Design is defined by a system with a design matrix, see equation (2), that cannot be rearranged as either a triangular or a diagonal matrix. A fully coupled design with two FRs can be exemplified with

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} DM_{1,1} & DM_{1,2} \\ DM_{2,1} & DM_{2,2} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \tag{7}$$

where $DM_{i,j} \neq 0$.

From this $FR_1$ and $FR_2$ can be stated as

$$FR_1 = DM_{1,1} DP_1 + DM_{1,2} DP_2 \tag{8}$$

$$FR_2 = DM_{2,1} DP_1 + DM_{2,2} DP_2 \, . \tag{9}$$

*Interaction effects* and *coupling* are fundamentally different. Equations (8) and (9) show that coupling in Axiomatic Design can be explained with an additive model, whereas equation (6) stresses that interaction effects are modeled by multiplying the values of the variables that interact, *A*C* in the example above, times the corresponding coefficient. The additive model prescribed by Axiomatic Design cannot express such a multiplication of variables, or DPs. See equation (1).

An expansion of Axiomatic Design's design equation is suggested below that will enable storage of interaction effects and pure quadratic terms with the Axiomatic Design notation. A second order multi response polynomial is suggested for this. The proposed equation builds upon Regression analysis (see Draper and Smith, 1998) and Response Surface Methods (Box and Draper, 1987; Myers and Montgomery, 1995).

Let's assume that the FR vector, **FR**, is a function of the DPs, plus error terms

$$\mathbf{FR} = f(\mathbf{DP}) + \boldsymbol{\varepsilon} \tag{10}$$

where **FR**= $[FR_1, FR_2, \cdots, FR_n]^T$, **DP**= $[DP_1, DP_2, \cdots, DP_n]^T$, and $\boldsymbol{\varepsilon}$ = the error vector $[\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_n]^T$.

A second order Taylor series expansion of equation (10) includes both interaction terms and pure quadratic terms. For a single FR this can be expressed as

$$\begin{aligned} FR_i &= \beta_0 + \beta_1 DP_1 + \beta_2 DP_2 + \cdots + \beta_k DP_k + \beta_{11} DP_1^2 + \cdots + \beta_{kk} DP_k^2 \\ &\quad + \beta_{12} DP_1 DP_2 + \beta_{13} DP_1 DP_3 + \cdots + \beta_{k-1,k} DP_{k-1} DP_k + \varepsilon \end{aligned}. \tag{11}$$

where $\beta_{kk}$ or $\beta_k$ = coefficients that determines the effect on $FR_i$ due to a change in the corresponding $k$ DP(s). $\beta_0$= intercept. $i \in \{1,2,\cdots,n\}$.

This expression can be generalized to the **FR** vector as

$$\mathbf{FR} = \{\mathbf{A_0}\} + [\mathbf{A}]\{\mathbf{DP}\} + \begin{Bmatrix} \mathbf{DP}^{\mathrm{T}}\mathbf{AH}_1\mathbf{DP} \\ \mathbf{DP}^{\mathrm{T}}\mathbf{AH}_i\mathbf{DP} \\ \vdots \\ \mathbf{DP}^{\mathrm{T}}\mathbf{AH}_n\mathbf{DP} \end{Bmatrix} \tag{12}$$

where **$\mathbf{A_0}$**= column vector of intercepts for the $n$ FRs, $[\beta_{0,1}, \beta_{0,2}, \cdots, \beta_{0,n}]^T$

**A**= the design matrix for FRs and DPs, see equation (2)

**$\mathbf{AH}_i$**= the matrix that forms the quadratic terms and their coefficient estimates, $b$, of $\beta$ in the second order polynomial for $FR_i$. It is a modified version of the Hessian matrix, $\left(\partial^2 FR_i / \partial DP_i \partial DP_j\right)$, and is defined as

$$\mathbf{AH}_i = \begin{bmatrix} \dfrac{\partial^2 FR_i}{\partial^2 DP_1} & \left(\dfrac{\partial^2 FR_i}{\partial DP_1 \partial DP_2}\right)\dfrac{1}{2} & \cdots & \left(\dfrac{\partial^2 FR_i}{\partial DP_1 \partial DP_n}\right)\dfrac{1}{2} \\ \left(\dfrac{\partial^2 FR_i}{\partial DP_2 \partial DP_1}\right)\dfrac{1}{2} & \dfrac{\partial^2 FR_i}{\partial^2 DP_2} & \cdots & \left(\dfrac{\partial^2 FR_i}{\partial DP_2 \partial DP_n}\right)\dfrac{1}{2} \\ \vdots & \vdots & \ddots & \vdots \\ \left(\dfrac{\partial^2 FR_i}{\partial DP_n \partial DP_1}\right)\dfrac{1}{2} & \left(\dfrac{\partial^2 FR_i}{\partial DP_n \partial DP_2}\right)\dfrac{1}{2} & \cdots & \dfrac{\partial^2 FR_i}{\partial^2 DP_n} \end{bmatrix}. \tag{13}$$

Similarly, equation *(12)* can be expressed for the DP-PV situation as

$$\mathbf{DP} = [\mathbf{B_0}] + [\mathbf{B}]\{\mathbf{PV}\} + \begin{Bmatrix} \mathbf{PV}^T\mathbf{BH}_1\mathbf{PV} \\ \mathbf{PV}^T\mathbf{BH}_i\mathbf{PV} \\ \vdots \\ \mathbf{PV}^T\mathbf{BH}_n\mathbf{PV} \end{Bmatrix}. \tag{14}$$

*Engineering application*: When combining Axiomatic Design with designed experiments as suggested in Figure 15 situations may arise when the experimenter, or designer, wants to store information about curvature and interaction effects with equation (13) or (14). For example, Derringer and Suich (1980) report a designed experiment with four response variables, or FRs. The experiment concerned Tire Tread and the FRs were: $FR_1$ PICO Abrasion Index [>120], $FR_2$ 200% Modulus [>1000], $FR_3$ Elongation at Break [$400<FR_3<600$], and $FR_4$ Hardness [$60<FR_4<75$]. The DPs were: $DP_1$ Hydrated silica level, $DP_2$ Silane coupling agent level, and $DP_3$ Sulfur level. The experiment was designed so that a second order polynomial could be fitted. Such a procedure requires, as shown above, an expansion of the current Axiomatic Design equation. One alternative is outlined in equation (12). The equations above also help store information from experiments with multiple responses (multiple objective functions, or FRs), with a notation from a systems engineering framework.

*Implications for Axiomatic Design theory*: Equations (12) and (14) indicate one solution approach to a specific problem and stress interesting research opportunities. For instance, do the axioms of Axiomatic Design have a bearing on the structure of $\mathbf{AH}_i$? Are specific properties of $\mathbf{AH}_i$ preferable over others? Are the axioms of Axiomatic Design valid with respect to second order FR-DP system models? Are there other, better and more intuitive, ways of expressing curvature and interaction effects within the Axiomatic Design framework?

It is hoped that the section above regarding *interactions* and *coupling* as well as equations (12) and (14) above will encourage future research on how to combine systems engineering methods with designed experiments.

## 3.3 COMPUTING THE PROBABILITY OF SUCCESS

Algorithms in this section present mathematical tools of calculating the probability of success (i.e. Information content) for decoupled designs. The presented methods show higher accuracy than simply summing the Information content of the design's functional requirements, which is current practice. The calculation methods thereby improve the possibility of choosing a correct design solution according to axiom 2. The methods also provide a tighter fit between efforts to increase robustness and efforts to decrease Information content, within the Axiomatic Design framework. Figure 17 describes the field of research for Paper C and how this section relates to different levels of scope for product development.

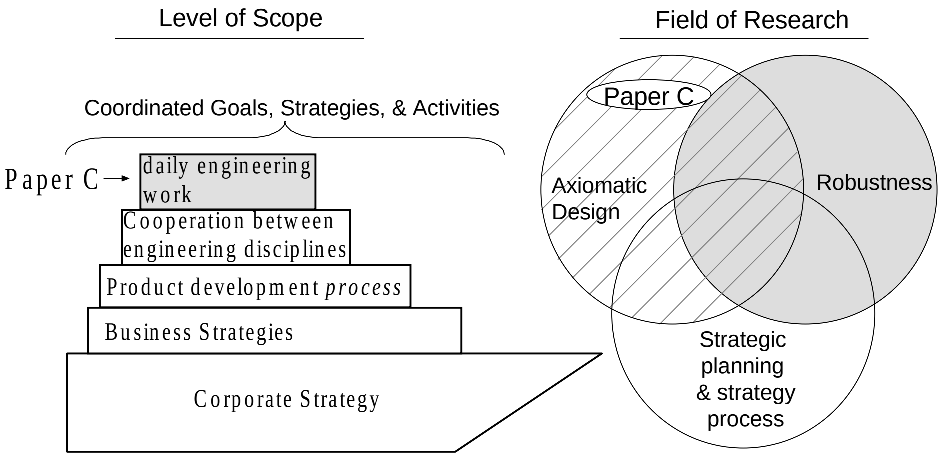


*Figure 17. How this section and its corresponding Paper C relate to different levels of scope for product development and the field of research.*

Robustness is closely related to the probability of success. Axiomatic Design focuses on selecting the design solutions with the highest probability of success, i.e. minimized Information content according to the second axiom. The difference between robustness improvements and decreased Information content by using designs or manufacturing processes that always perform within their tolerances stems from the quadratic loss function. The quadratic loss function is further explained in Figure 9 and Figure 10, and Section 2.2.

Although Axiomatic Design does not specifically address all issues related to robust design (see "Research related to Paper C" at the end of this section), it provides a probabilistic view of design and seeks to incorporate quality improvement tools in the design process (Suh, 1990; Suh, 1992; Suh, 1995; Suh, 1999). The probabilistic view of design and the goal of minimizing the Information content have complementary properties with robustness improving efforts. Combining designed experiments that focus on variance minimization and robustness improvements with Axiomatic Design is discussed in Suh (1990). Furthermore, a robust design solution has, in most cases, the lowest Information content (for certain exceptions, see "Research related to Paper C" at the end of this section).

The axioms of Axiomatic Design guide the design process. The Information axiom helps in choosing the design with the highest probability of success (i.e. the design with the lowest Information content) among the solutions that satisfies the independence axiom (i.e. decoupled or uncoupled solutions).

When working with Axiomatic Design in order to improve product quality and robustness, both the Information content and some measure of robustness need to be computed.

Traditionally, Information content ($I$) in decoupled designs with probabilistically independent design parameters has been computed according to equation (15) below (Albano and Suh, 1993; Suh, 1999):

$$I = \sum_{i=1}^{n} \log\left(\frac{1}{p_{si}}\right) \tag{15}$$

where

$p_{si}$ is the probability of success for design parameter $i$ in a design consisting of $n$ design parameters.

Equation (15) is developed from the more general form of computing Information content described in equation (16). Equation (16) is based on Shannon's theory of communication (1948) and Wilson's work on complexity in Axiomatic Design (1980).

$$I = \log\left(\frac{1}{p_{si}}\right) \tag{16}$$

Based on the above identified need for and current practice in computing Information content when working with quality improvements in Axiomatic Design, the following research question and hypotheses are addressed:

Research question 3: *Is summing of the Information content of functional requirements (FRs) in a decoupled design a proper way to calculate the aggregate Information content of the design?*

*Hypothesis 3.1*: Adjusting the current calculation of Information content for correlation among FRs, in the case of decoupled multi-FR designs, would increase the accuracy of the estimated Information content compared to simply summing the Information content of the various FRs. This method of calculating Information content for decoupled designs would thereby improve the possibility of choosing the correct design solution according to Axiom 2.

*Hypothesis 3.2*: The proposed method estimates the Information content of decoupled designs with less accuracy than the current method of summing the Information content of the various FRs.

The research method for testing hypothesis 3 is based on formal proofs and computer simulations, and is described in Paper C.

It is found in Paper C that the covariance matrix for the functional requirements ($\mathbf{K}_{\mathbf{FR}}$) is non-diagonal for decoupled design solutions with statistically independent DPs. Since $\mathbf{K}_{\mathbf{FR}}$ is non-diagonal, the functional requirements are not probabilistically independent. The non-diagonal structure of $\mathbf{K}_{\mathbf{FR}}$ is due to the decoupled design solution. Functional requirements that are not probabilistically independent prohibit the use of equation (15) (see Theorem 13, page 154 in Suh, 1990).

Two methods for computing Information content in decoupled designs are therefore developed and tested in Paper C. These methods take correlation between FRs into account. The first method is based on a general case, where the probability of success of a design is the integral of the joint density function of a vector of design parameters $f(\mathbf{DP})$ over the design range:

$$p_s = \int_{\text{design range}} f(\mathbf{DP})d\mathbf{DP} \qquad (17)$$

where $p_s$ is the probability of success for the design system.

It is found that taking a decoupled design matrix into account extends equation (17) to

$$p_s = \int_{\substack{\text{Lower}\\\text{tolerance}\\\text{limit for}\\\text{DP1}}}^{\substack{\text{Upper}\\\text{tolerance}\\\text{limit for}\\\text{DP1}}} \int_{\substack{\text{Lower tolerance}\\\text{for DP2, as } f\text{(DP1,}\\\text{Design Matrix,}\\\text{FR2)}}}^{\substack{\text{Upper tolerance}\\\text{for DP2, as } f\text{(DP1,}\\\text{Design Matrix,}\\\text{FR2)}}} \cdots \int_{\substack{\text{Lower tolerance}\\\text{for DPn, as } f\text{(DP1,}\\\text{DP2,}\cdots\text{,DPn-1,}\\\text{Design Matrix, FRn)}}}^{\substack{\text{Upper tolerance}\\\text{for DPn, as } f\text{(DP1,}\\\text{DP2,}\cdots\text{,DPn-1,}\\\text{Design Matrix, FRn)}}} f(\mathbf{DP_1},\mathbf{DP_2},\ldots\mathbf{DP_n})\,d\mathbf{DP_n}\ldots d\mathbf{DP}_2\,d\mathbf{DP}_1$$

or,

$$p_s = \int_{\frac{-\tau\mathbf{FR}_1+\delta\mathbf{FR}_1}{\mathbf{A}_{1,1}}}^{\frac{\tau\mathbf{FR}_1+\delta\mathbf{FR}_1}{\mathbf{A}_{1,1}}} \int_{\frac{-\tau\mathbf{FR}_2+\delta\mathbf{FR}_2+\mathbf{A}_{2,1}\mathbf{DP}_1}{\mathbf{A}_{2,2}}}^{\frac{\tau\mathbf{FR}_2+\delta\mathbf{FR}_2-\mathbf{A}_{2,1}\mathbf{DP}_1}{\mathbf{A}_{2,2}}} \cdots \int_{\frac{-\tau\mathbf{FR}_n+\delta\mathbf{FR}_n+\sum_{i=1}^{n-1}\mathbf{A}_{n,i}\mathbf{DP}i}{\mathbf{A}_{n,n}}}^{\frac{\tau\mathbf{FR}_n+\delta\mathbf{FR}_n-\sum_{i=1}^{n-1}\mathbf{A}_{n,i}\mathbf{DP}i}{\mathbf{A}_{n,n}}} f(\mathbf{DP}_1,\mathbf{DP}_2,\ldots,\mathbf{DP}_n)\,d\mathbf{DP}_n\ldots d\mathbf{DP}_2\,d\mathbf{DP}_1 \quad (18)$$

where (equation (18) is presented in more detail in Paper C):

$\tau FR_j$ is the target value of the $j^{th}$ FR

$\delta FR_j$ represents the bilateral tolerance for the $j^{th}$ FR

$A_{ij}$ is the i-$j^{th}$ element of the Design Matrix.

Equation (18) applies only if all the on-diagonal elements of the design matrix are positive. For any negative on-diagonal elements, the upper and lower limits of integration for the corresponding DP must be switched.

Once the probability of success is computed, the Information content can be calculated with equation (16).

The computational complexity of deterministic numerical integration of equation (18) grows non-polynomially with the number of DPs. If the Information content of a design with many DPs is to be computed, it is often more computationally efficient to use a non-deterministic integration technique such as the Monte Carlo method.

A second method for computing Information content of decoupled designs with many DPs is also developed for the special case of uniformly distributed DPs.

The methods of calculating Information content presented above and in Paper C are applied to a computer simulation of a case study of two proposed network designs for passive filters. The filter case study was first described in Suh (1990). The computational correctness of the two methods developed is compared to the Monte Carlo approach to calculating the Information content. Information content is calculated for DPs assumed to be either normally distributed or uniformly distributed.

The results from the Monte Carlo simulation approach and the equation (15) approach are almost identical, lending further evidence that equation (18) is correct. Also, the methods presented in Paper C for calculating Information Content in decoupled designs (see, for instance, equation (18) above) correctly suggest another design solution than that suggested by the approach described in equation (15) above.

*Conclusion*: Based on the findings described above and in Paper C, hypothesis 3.2 is rejected.

Hypothesis 3.1 is accepted, based on the formal proofs and simulations. Thus, adjusting the current calculation of Information content for correlation among FRs, in the case of decoupled multi-FR designs, does increase the accuracy of the estimated Information content compared to simply summing the Information content of the various FRs.

However, it is hoped that the approach described above will be further improved, revised and used in future research.

Summary: This section and Paper C show that equation (15) is only valid for uncoupled designs, and an extended equation that considers correlation among functional requirements is needed for decoupled designs. Information content in decoupled designs is calculated by first computing $p_s$ with equation (18) and thereafter computing the Information content using equation (16), with $p_{si} = p_s$.

A method for computing Information content in the special case of uniformly distributed DPs in decoupled designs is also developed in Paper C.

- **Research related to Paper C**

Section 3.3 is based on the Axiomatic Design framework, the goal of the section being to improve the Axiomatic Design theory for practitioners interested in robustness improvements as well as the closely related issue of the probability of success of a design.

Assumptions of Axiomatic Design that are important to clarify, as well as areas of improvement for Axiomatic Design's current mathematical formulation of the second axiom, include the following:

1. Probabilistically independent DPs are often assumed. Probabilistically independent DPs are not always the case in manufacturing systems. For instance the features on electronic Chips are probabilistically dependent. Steps in Chemical processes might also be probabilistically dependent. Mathematical tools for easy calculation of Information content with probabilistically dependent DPs are needed.
2. Current application of Information content alone according to equation (16) and axiomatic design theory cannot separate the design situations in Figure 18 and Figure 19.

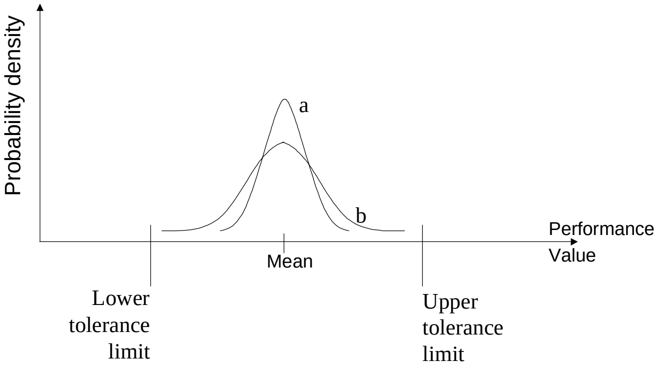


*Figure 18. Information content is zero for both designs, even though design (a) is more robust.*

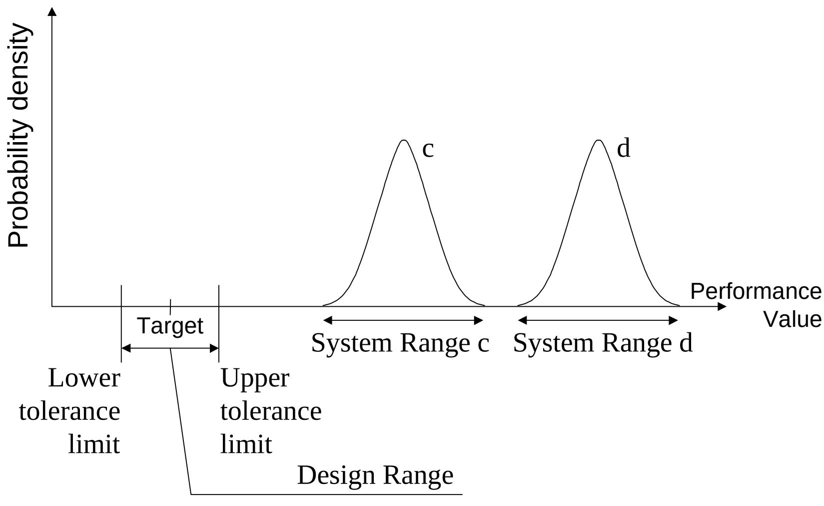


*Figure 19. Information content is infinity for both designs (c) and (d), even though design (c) is closer to target.*

Both Figure 18 and Figure 19 identify situations where the current practice in Axiomatic Design lacks the ability to identify the best design solution, or in the case of Figure 19 the least bad solution. Depending on how Axiomatic Design theory is interpreted, it might be stated that Figure 19 shows a situation that is never acceptable, since both design solutions are outside the tolerance limits. Nevertheless, Figure 18 describes a situation where robustness improvements pass unidentified unless the mathematical formulation of the second axiom is complemented with some means of accounting for the quality loss function (see Figure 10).

Further research is necessary to improve the mathematical formulation of the second axiom in order to resolve the situations described in Figure 18 and Figure 19.

Although Figure 18 exemplifies a situation where the Information content and the second axiom do not distinguish between a robust design and a less robust design, most industrial design situations can be described with Figure 20, where the Information content of Axiomatic Design *does* select the most robust solution.

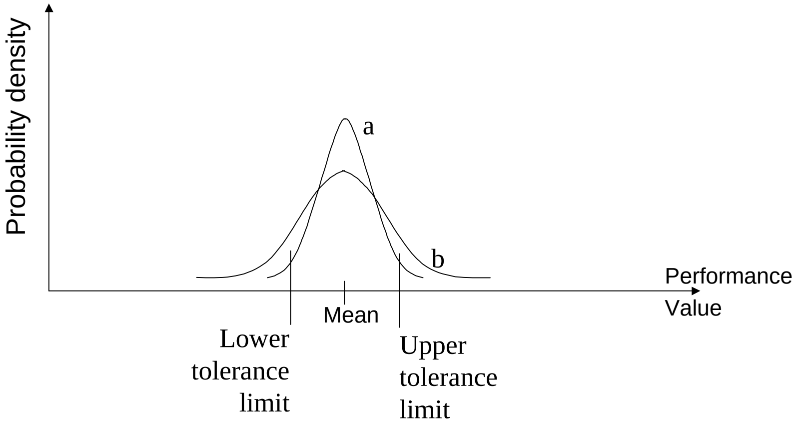


*Figure 20. The most robust design (a) has the lowest Information content and is preferable to design (b) according to axiom 2 of Axiomatic Design.*

3. Uniform distributions are often assumed when working with Axiomatic Design. Practical tools for dealing with other probability density functions need to be developed.

## 3.4 COMPUTING THE ECONOMIC VALUE OF A SYSTEM'S ROBUSTNESS

In this section an equation for computing quality loss in multi-FR designs is presented. The relationship between the form of the design matrix in Axiomatic Design and the system's quality loss is also investigated. This research is further detailed in Paper D. The scope and field of research in Paper D and this section are presented in Figure 21. A combination of quality loss and Information content that overcomes some of the limitations of the Information content that was stressed in section 3.3 is presented at the end of the section.

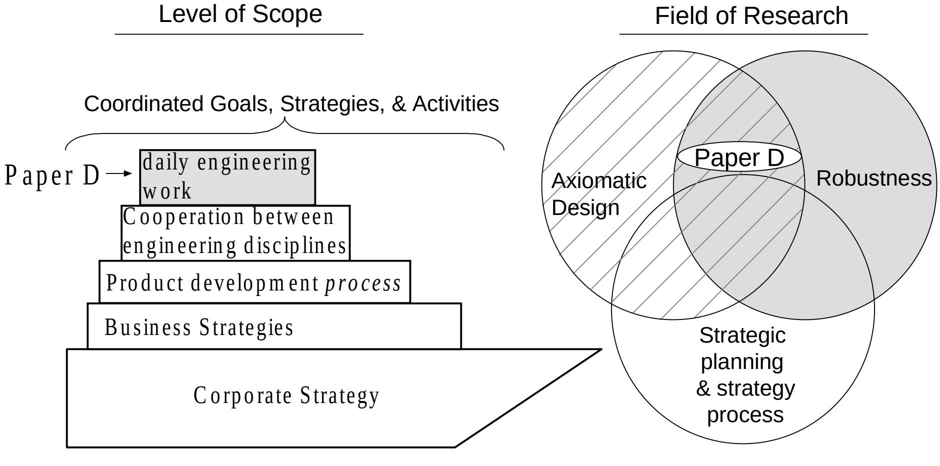


*Figure 21. How this section and its corresponding Paper D relate to different levels of scope for product development and the field of research.*

Engineering design decisions have a large bearing on the economy of industrialized firms. In most situations the company wants to maximize the expected economic value of such decisions. Obtaining the economic value of a design concept, or design alternative, is a multifaceted engineering problem including for instance product/engineering, market, financial, legal, and ethical aspects. Robustness is an important aspect of product quality and is one of these aspects.

The ability to express the economic value of a design alternative's robustness in terms of Axiomatic Design would strengthen the link between these fields of research. It would also enhance the applicability of Axiomatic Design and robust design in system development and procurement, especially as part of determining the expected value of engineering design decisions.

Research question 4: *How can the economic value of robustness be expressed and evaluated by applying the tools and methods of Axiomatic Design?*

Research question 4.1: *What is the relationship between the form of Axiomatic Design's design matrix, i.e. coupled/decoupled/uncoupled, and the economic value of robustness?*

The hypothesis related to research question 4.1 is:

*Hypothesis: 4.1*: Applying Taguchi's quality loss concept to Axiomatic Design will allow for evaluation of robustness and will show that *uncoupled* systems are more robust and *cause less quality loss* than decoupled and coupled systems.

Below follows a short summary of the results presented in Paper D.

The economic value of robustness for a system can be expressed as quality loss, *L(system)*, and it can often be assumed to be the sum of the individual *FRs'* quality losses. See equation (19).

$$L(system) = \sum_{i=1}^{m} L(FR_i) \tag{19}$$

where $m$= number of FRs in the system.

L(system) can also be expressed in terms of tangible design parameters, DPs. See equation (20). Equation (20) is derived by combining equation (4) and (1) with equation (19). Assuming that controllability is not an issue allows for elimination of the bias term in equation (4).

$$
\begin{aligned}
L(system) &= \sum_{i=1}^{m} L(FR_i) \\
&= \sum_{i=1}^{m} k_i Var(FR_i) \\
&= \sum_{i=1}^{m} k_i \sum_{j=1}^{n} A_{ij}^2 Var(DP_j) \\
&= \sum_{j=1}^{n} \left( \sum_{i=1}^{m} k_i A_{ij}^2 \right) Var(DP_j)
\end{aligned}
\qquad (20)
$$

where $n$= number of DPs in the system, or columns in the design matrix.
$m=n$ in a system with equally many FRs as DPs.
$k_i$ = quality loss coefficient for $FR_i$.
$A_{i,j}$ = the $i,j$th matrix element of the design matrix, **DM**, in equation (2).

Equation (20) provides a relationship between the quality loss and the design matrix, **DM** or **A**, and shows that the quality loss of a system, if we can ignore bias, is not dictated by the degree of coupling of design matrix, i.e. uncoupled/decoupled/coupled. The machine concept example in Paper D exemplifies this by showing that a coupled design and an uncoupled design can have identical quality loss.

*Conclusions*: Equation (20) presents a tool for calculating the economic value of robustness in terms of quality loss for a system. This quality loss is computed using the information stored in Axiomatic Design's design matrix and it is the loss due to variance in the DPs.

Based on the findings described above and in Paper D, hypothesis 4.1 is rejected. There is no clear relationship between the degree of coupling in Axiomatic Design, i.e. coupled/decoupled/uncoupled design matrices, and the economic value of robustness in terms of quality loss.

It is hoped that the presented equation (20) will enhance the ability to express the economic value of engineering systems. Furthermore, the presented tool may form an initial step towards a larger framework of metrics that helps evaluate the expected economic value of engineering design decisions. Improvements and applications of the presented findings are encouraged.

- **Research related to Paper D**

One way of decoupling a system that will guarantee increased robustness and lower quality loss is elimination of unwanted off-diagonal elements in the design matrix without effecting on-diagonal elements. Such a decoupling will decrease the contribution to *L(system)* from

$$\left(\sum_{i=1}^{m} k_i A_{ij}^2\right)$$

in equation (20). This will always decrease *L(system)* since equation (20) is a summation of terms ≥ 0, assuming $k_i \geq 0$.
This kind of decoupling is outlined in Figure 22 together with a decoupling that also effects the diagonal elements and may lead to both higher and lower quality loss.

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \Rightarrow \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \text{ Always more robust}$$

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \Rightarrow \begin{bmatrix} A'_{11} & 0 \\ 0 & A'_{22} \end{bmatrix} \text{ More/less robust?}$$

*Figure 22. Only removal of off-diagonal terms without effecting on-diagonal terms guarantees improved robustness and less quality loss when decoupling a design.*

How to achieve decoupling of designs without effecting diagonal elements is probably very tricky. The design change may be viewed in terms of contradictions whereby the TRIZ method (Altshuller, 1988) could be helpful. Further research on this topic is necessary. However, equation (20) provides a tool for evaluating quality loss for both kinds of decoupling described in Figure 22.

Many of the limitations of the Information content, *I*, related to evaluation of design concepts could be overcome by combining *I* and quality loss, *L*. Some limitations of *I* are mentioned in section 3.3. Safety limits, *s*, could define the safety range that the designer wants the design to perform within at a certain level of probability, $p_{\text{safety level}}$. See Figure 23 for a one-dimensional outline. If we assume that a design must satisfy all of its *FRs* simultaneously at $p_{\text{safety level}} \geq 0.6$, then a graphical inspection indicate that concepts (d), (e), and (f) in Figure 23 all fail to meet this constraint. The Information content approach applied to this situation could be called, $I_{safety}$, and corresponds nicely to such a goal post mentality. Evaluating the concept's robustness in terms of *L* will focus on variance minimization and is furthermore able to distinguish between concepts (a) and (b), which now are distributed inside the acceptance limits of the $I$ calculation. This separation of (a) and (b) could not be carried out by $I_{safety}$. Equation (20) helps determine $L$ for the design alternatives. The tolerance limits, $t_i$, are set based upon economic trade-offs between increased costs in manufacturing due to tighter tolerances and decreased $L$ due to reduction in performance variation. $\left|\text{Target} - t_i\right| \leq \left|\text{Target} - s\right|$ and should be defined for the $i$ design concepts separately.

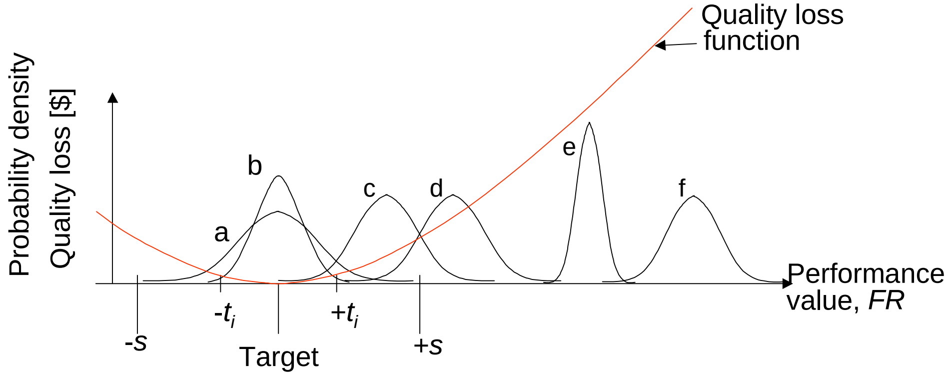


*Figure 23. Combining Information content, I, and Quality Loss, L, overcomes limitations that stem from applying I and L in isolation.*

To summarize, $I$ could be used to constrain the solution space, and $L$ could be applied to select and optimize concepts that perform at acceptable probabilistic safety levels.

A note on theorem 9, "Design for Manufacturability" in Suh (1990): The example in Paper D with two axis tilted 45° shows a manufacturing machine concept that is coupled and still will be able to manufacture products. The coupled system represents, in this case, a linear equation system with two unique equations with two unknowns. This equation system can be solved and the product can be manufactured. In general, if the design equation expressed in equation (1) consists of $m$ FRs and $n$ DPs and $m$=$n$, then the system has exactly one solution, $\mathbf{DP} = \mathbf{DM}^{-1}\mathbf{FR}$, for every invertible **DM**. Hence, theorem 9 is not correct since it states that if at least one of the design matrices represents a coupled design, the product cannot be manufactured. In many cases coupled systems are manufacturable, but undesirable for other reasons.

## 3.5 MULITIVARIATE ROBUSTNESS

Two methods for feature selection in robust multivariate classification are compared in this section. Classification is often applied in manufacturing with on-line quality control by machine vision to sort out good products from bad ones. Two examples of other areas where classification is applied are target recognition, and medical screening. The presented research is detailed in scope and addresses the research field of robustness. See Figure 24 and Paper E.

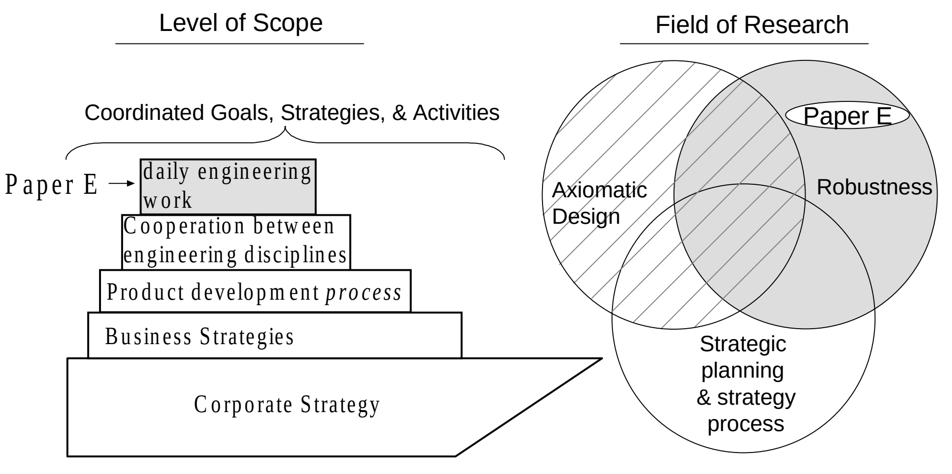


*Figure 24. How this section and its corresponding Paper E relate to different levels of scope for product development and the field of research.*

Mahalanobis Taguchi System (MTS) has been an increasingly popular research topic in the Robust Design community during the last couple of years, and very good results are reported with MTS (Frey, 1999; Matsuda et al., 1999; Nagao et al., 1999; Taguchi and Jugulum, 1999).

A study was performed to compare MTS with the tools and techniques present in more “classical” approaches to multivariate statistics and classification ( for instance Chen and Wang, 1999; and Johnson and Wichern, 1998). The underlying assumption was that utilizing the statistical information stored in the training populations, that most classification methods rely on, would improve feature selection for robust classification compared to the MTS approach.

Research question 5: *How effective is the Mahalanobis Taguchi System (MTS) applied to multivariate robust classification compared to an approach that selects features for the classification based on a principal component transformation of the data set combined with a multimodal overlap measure (PFM)?*

*Hypothesis 5.1*: The feature selection based on the Mahalanobis Taguchi System (MTS) will always yield a classification more robust to disturbances with larger signal-to-noise ratios and fewer classification features compared to a feature selection based on PFM. MTS will also achieve equally good, or better, classification performance than PFM.

*Hypothesis 5.2*: The feature selection based on the Principal component Feature overlap Measure (PFM) will always yield a classification more robust to disturbances with larger signal-to-noise ratios and fewer classification features compared to a feature selection based on MTS. PFM will also achieve equally good, or better, classification performance than MTS.

The comparative study is based on an initial study by Frey (1999) where he combined a wavelet transformation (see Strang and Nguyen, 1997) of a simulated machine vision picture with MTS. Four pictures of fine art simulate four different products that the machine vision system shall distinguish between. Noises are imposed as (1) inverting the picture or changing the pictures' pixels with (2) snow, (3) blurring, and (4) shifting. Each noise had a certain probability of occurrence. For details see Paper E. Figure 25 outlines the approach and the shaded text areas indicate where new research was performed through the comparative study.

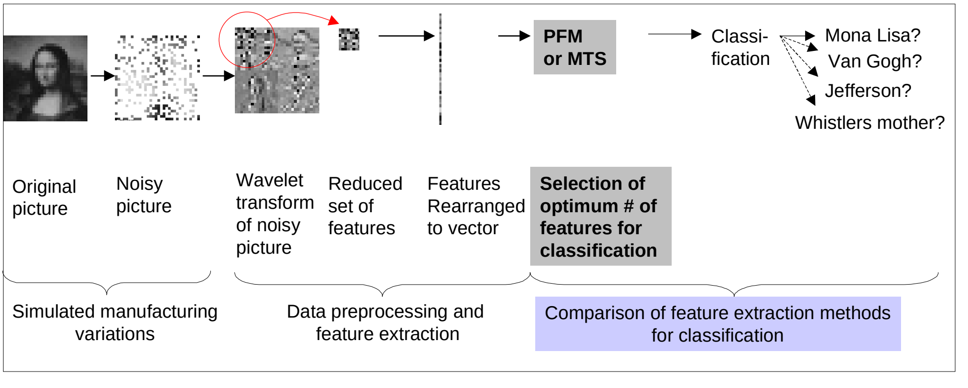


*Figure 25. Comparing two different ways of selecting the optimum features for classification in the presence of noise.*

It is found that the feature selection based upon PFM is more robust to low quality pictures and achieves significantly higher signal-to-noise ratios (+80dB) than MTS. PFM also selects features to base the classification on that gives equal or better classification performance compared to MTS with a lower number of classification features (-75%).

All technical details of the results and conclusions are omitted in this initial presentation of the research and can be found in Paper E. The reader interested in the PFM and MTS methods, as well as a short introduction to classification, is also referred to Paper E.

*Conclusion*: Based on the findings described above and in Paper E, hypothesis 5.1 is rejected. To summarize, the classification based on a principal component transformation of the data set combined with a multimodal overlap measure (PFM) yields equal or better classification performance, a more robust classification, and uses fewer features than the Mahalanobis Taguchi System (MTS) classification.

Hypothesis 5.2 states that a feature selection based on the Principal component Feature overlap Measure (PFM) always yields a classification more robust to disturbances with larger signal-to-noise ratios and fewer classification features compared to a feature selection based on MTS. Furthermore, PFM should also achieve equally good, or better, classification performance than MTS.

Hypothesis 5.2 *cannot* be proven since the comparison is based on a single documented case. Though, the favorable performance of PFM in the comparative study makes the approach an attractive alternative compared to MTS. Further comparisons based on other kinds of data sets are needed to strengthened hypothesis 5.2.

*Multivariate classification methods must often be tailored for the specific problem and a single method is probably not to prefer in all situations (see for instance Johnson and Wichern, 1998). The presented research shows that this is the case also for MTS and it presents an attractive competing approach to feature selection for robust classification that hopefully will be effective in many industrial applications. It should be noted that both MTS and PFM perform well.*

## 3.6 COMPARING EXPERIMENTAL METHODS FOR ROBUSTNESS

The orthogonal arrays (OA) of the Taguchi Method is in this section compared to the experimental strategy of changing factors one-at-a-time (OAT). It is found that the one-at-a-time strategy in many situations outperforms orthogonal arrays. The research presented in this section summarizes the research in Paper F. Focus is on experimental methods for increased robustness at a fairly detailed level of scope. See Figure 26. A short introduction to the Taguchi Method is presented in Appendix G for the reader with limited knowledge of this method's experimental strategy and how orthogonal arrays are applied.

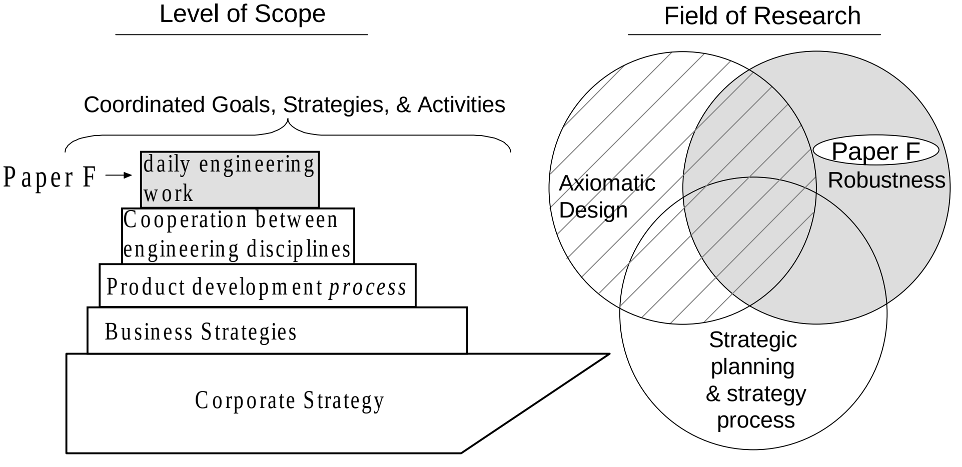


*Figure 26. How this section and its corresponding Paper F relate to different levels of scope for product development and the field of research.*

It is found that far from all industrial companies systematically work with robustness improvements (Jugulum and Dichter, 2001) and roughly 40% of all initiated experiments are aborted before they are fully completed. Very often time and schedule changes force the experimenter to abort the experiment, or the experimenter may simply be satisfied with the results achieved so far and therefore prefers to focus his/her recourses elsewhere. Further education in robust design is necessary, but one also *has to accept the current situation and develop methods and tools that are more user friendly and adjusted to fit basic principles of human and organizational behavior without loosing the current approaches ability to produce good results.*

Based on the above mentioned and problems and challenges the following research question and hypotheses were formulated:

Research question 6: *How effective is the one-at-a-time experimental strategy (OAT) compared to the Taguchi method's orthogonal arrays in terms of (1) signal-to-noise ratio improvement rate, (2) total signal-to-noise ratio improvement, (3) the number of experiments or calculations that have to be performed, as well as (4) the cost associated with changing factor levels?*

*Hypothesis 6.1*: The one-at-a-time strategy (OAT) will yield a faster signal-to-noise ratio improvement rate, equal or larger total signal-to-noise gain, fewer total experiments, and lead to lower costs related to factor level changes compared to the Taguchi Method's orthogonal arrays (OA).

*Hypothesis 6.2*: Orthogonal arrays (OA) will yield a faster signal-to-noise ratio improvement rate, equal or larger total signal-to-noise gain, fewer total experiments, and lead to lower costs related to factor level changes compared to the one-at-a-time strategy (OAT).

The three main theoretical reasons for why OAT should be appealing and useful compared to orthogonal arrays in today's industry are: (1) decrease in experimental error, or improved equipment for robustness optimization experiments; (2) humans and organizations tend to "satisfice" not "optimize", which explains why many experiments are aborted when good enough results are achieved, or when the experimental context changes (for instance changed experimental budgets and time frames); (3) costs of changing factor levels. Points (1) and (2) are stressed in Figure 27 below.

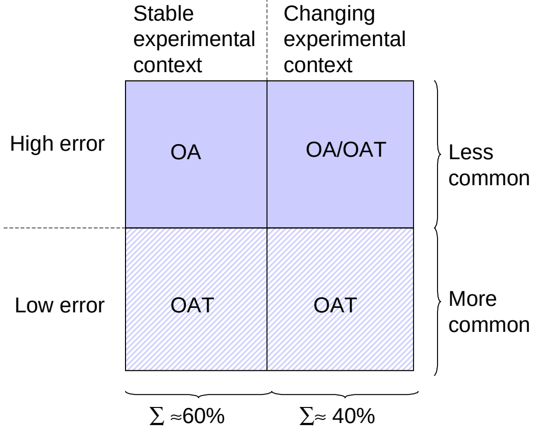


*Figure 27. Low experimental error and a changing experimental context relatively common. Experimental method preferred for a certain situation indicated (only valid for comparing OAT and OA).*

A computer simulation of a Wheatstone Bridge system was performed to test hypotheses 6.1 and 6.2. In OAT the control factors are changed one at a time, and once all levels of a factor are investigated in terms of robustness then the most robust level is kept in the subsequent experimental runs. OAT is briefly outlined in Figure 28.

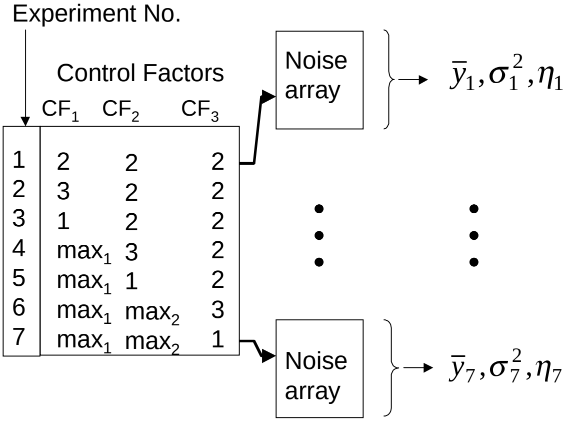


*Figure 28 One-at-a-time strategy (OAT), exemplified with a three control factor, at three levels, inner array.*

The result from Paper F is summarized below. OAT provides a faster improvement rate of confirmed signal-to-noise ratios than OA for the tested system. Hence, OAT yields better robustness improvements if the designed experiment is aborted before it is finished. The total robustness improvement from OAT is at least as good as the result obtained by OA. Fewer runs, or computations, are needed to carry out the designed experiment with OAT compared to OA. For the Wheatstone Bridge system OAT requires 198 computations compared to OA's 342 runs. Estimations of costs with regards to changing factor levels, if this is an issue, show that OAs are between two and five times more expensive than OAT. To summarize, OAT outperforms OA in the investigated example.

Additional experimental runs can be added to OAT if the experimenter wants to expand the predictive system model. Confounding can, for instance, be resolved relatively easy if the experimenter is not satisfied with the results and wants to study control-by-control factor interactions.

OAT can in many situations directly replace OAs as the method and tool of choice within the Taguchi Method.

*Conclusion*: Based on the findings described above and in Paper F, hypothesis 6.2 is rejected, since the one-at-a-time strategy (OAT) in the Wheatstone Bridge simulation outperforms the Taguchi Method's orthogonal arrays (OA).

Hypothesis 6.1 is valid for the documented system. The favorable performance of OAT in the comparative study makes hypothesis 6.1 likely to hold true also in many other situations. Furthermore, the initial results from the comparative study seem to be generalizable from a theoretical viewpoint in situations with relatively low experimental error, or low experimental error in comparison to the induced noise. Further comparisons based on systems with different degrees of interaction effects as well as different levels of experimental errors are needed to further quantify the kinds of situations when hypothesis 6.1 is valid.

Hypothesis 6.1 states that the one-at-a-time strategy (OAT) will yield a faster signal-to-noise ratio improvement rate, equal or larger total signal-to-noise gain, fewer total experiments, and lead to lower costs related to factor level changes compared to the Taguchi Method's orthogonal arrays (OA).

*It should be stressed that OAT is no magical solution and that there is no experimental strategy that is optimal in every experimental context. See related research below.*

- **Research related to Paper D**

Table 2 presents a qualitative comparison of OAT, the Taguchi Method with OA, and the Response Surface Methodology (RSM) applied for robustness improvements. The table focuses on how well suited the methods are for different experimental situations. The comparison above has not included the RSM. RSM is the major experimental school for robustness optimization, besides the Taguchi Method, and is often preferred in academia. RSM applied for increased robustness often models the mean and the variance separately. Predictive models built by RSM most often include studies of interactions. It would be misleading to carry out the comparison of OAT and OA above, without mentioning RSM. We therefore include RSM in Table 2. The table is intended to serve as advice when selecting an appropriate method for a particular experimental context. The table further emphasizes the fact that non of the compared methods is superior in every aspect.

*Table 2* *Qualitative comparison of experimental strategies for robustness improvements.*

| | | Robustness improving method | | |
|---|---|---|---|---|
| **Aspect of comparison** | | One-at-a-time strategy (OAT) | Taguchi Method with OA | RSM, for robustness |
| 1. | Can method tackle additive systems? | ++ | ++ | ++ |
| 2. | Can check for *presence* of interactions? | ++ | ++ | ++ |
| 3. | Can estimate interaction effects? | -[2] | +[1] | ++ |
| 4. | Experimental cost related to *number of runs?* | + | - (high cost) | +[6] |
| 5. | Experimental cost related to *change of factor levels*?[4] | ++(low cost) | + | - |
| 6. | Fidelity of explaining model for robustness optimum? | + | + | ++ |
| 7. | *Confirmed* robustness improvement if experiment is aborted half way through? | ++ | + | -[3] |
| 8. | Applicable for follow-up experiments for future improvements? | + | - | ++ |
| 9. | Provides predictive model? | + | + | ++ |
| 10. | Level of Statistical knowledge required to apply method | ++ (low) | + | - (high) |
| 11. | Ability to tackle large experimental measurement errors | - | + | ++[5] |

[1] *Only* if they are suspected *before* experiment.
[2] If they are suspected *before* experiment. Though, it is possible to resolve confounding patterns by additional runs. Further research necessary before easy to use tools are available for this.
[3] Assumes randomization technique applied and noises included in inner array.
[4] Only applicable for systems where there are costs associated with level changes.
[5] Assumes randomization technique.
[6] Mixed resolution experimental RSM designs (see for instance Myers and Montgomery, 1995) may allow the experimenter to trade estimations of control-by-noise interactions for estimation of control-by-control interactions or reduced number of experimental runs. This requires *a priori* knowledge about factors that have no effect on robustness (i.e. non-active control-by-noise interactions). Thus, RSM may in some situations provide increased flexibility and reduced number of experimental runs that would lead to a '++' rating.

# 4 FUTURE RESEARCH

It would be interesting to further verify and apply the findings presented in this thesis (see Section 3 and Papers A, B, C, D, E, and F). The author is especially interested in applying the findings in Paper E to real life manufacturing problems, as well as to further study the one-at-a-time experimental strategy's (OAT) sensitivity to high levels of pure error.

# 5 CONCLUSION

This thesis presents six major tools and methods for robust product development at different levels of scope within a company: (1) Axiomatic Design is used as a tool for customizing and designing company strategies and processes [by aligning high and low level goals, strategies, and activities, the tool seeks to help companies achieve coordination, structure and effective planning, thereby enabling faster and cheaper product development processes. This tool was successfully tested in one industrial case study]; (2) using a combined approach of design object analysis performed with Axiomatic Design, Quality Control tools, and designed experiments seems to be a fruitful way of increasing product performance and robustness [a successful automotive case study illustrates this]; (3) a method for computing Information content in decoupled designs is developed and provides more accurate estimations of which design concept, among many alternatives, has the highest probability of success; (4) a tool for computing the economic value of a system's robustness due to variation in the design parameters combines Axiomatic Design's system modeling with Taguchi's quadratic loss function; (5) a tool for selecting features for multivariate robust classification; (6) a clarification of how, and when, the one-factor-at-a-time strategy can be applied for improved robustness in designed experiments.

Tools and methods in examples (1) and (2) above have fulfilled the goal of being usable in practice in industry (see Papers A and B). The remaining methods and tools are developed in an academic environment (see Papers C, D, E, and F). Although the simulated examples in these papers indicate industrial relevance and practical usability, further research is needed in order to establish the practical usability of these methods in industry. Nevertheless, these approaches provide theory development in the fields of Axiomatic Design and Designed Experiments.

The presented research covers the spectrum from tools for high strategic levels of product development down to specific tools for engineering problem solving and computing.

Writing and performing the research presented in this thesis has been a significant learning experience for the author, indeed far more so than was anticipated when research started.

It is hoped that the tools and methods presented in this thesis will stimulate a robust and more probabilistic view of product development. The author would be delighted if the presented research also stimulates related research and improvements of the presented findings that will increase knowledge about robustness in product development.

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