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Extended Application of Robust Design Methodology

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ABSTRACT

Robust Design Methodology (RDM), a subset of Quality Management (QM), is an approach applied to the design phase of product development in order to manage variability in product performance by creating insensitivity to noise factors. Noise factors are sources of variation that cannot be readily controlled. RDM is an approach that can be characterized by principles, practices and tools. The main principles of RDM include an awareness of variation and creating insensitivity to noise factors. Further, it is necessary to continuously apply the main principles of RDM throughout product development. Previous research on RDM has mainly focused on the design stage of product development, i.e. the front-end, and on the application of front-end design tools. There is a lack of RDM practices focusing on the back-end of product development. RDM, if applied continuously to product development, can contribute to reduced scrap and waste. At the same time, industries face the challenge of addressing sustainability considerations in product development. One way to face this challenge is to integrate sustainability considerations into existing methodologies and tools, such as QM, as an approach towards sustainable product development (SPD). The purpose of this thesis is to contribute to an extended application of RDM by using back-end data for front-end improvement and by exploring how RDM might contribute to SPD.

The empirical setting of the case study was a medium-size Swedish manufacturer. Customer claims data at the organization constituted the back-end data of product development. The principal data collection method involved semi-structured interviews supported by a review of internal documents and the claims database. Other methods included participant observations and the compilation of unstructured verbal information through an affinity exercise. Exploratory Data Analysis (EDA) was used for the quantitative analysis of claims data. Further, to understand and clarify the contribution of RDM efforts towards SPD, a conceptual study was carried out by reviewing and comparing the underlying theoretical ideas of RDM and SPD.

Possible front-end improvements were suggested by the use of back-end data in two major ways: first, a systematic analysis of claims data tied to a problem-solving tool such as Failure Mode and Effects Analysis (FMEA); second, analysis of claims data based on a product life cycle approach to identify possible noise factors in all stages of a life cycle. Both practices contributed to the continuous applicability of RDM throughout product development and product life cycle stages. Further, the identification of noise factors in product life cycle stages was one way in which RDM efforts might contribute to SPD. The conceptual study resulted in possible links between RDM and sustainability.

The extended application of RDM by the use of back-end data for front-end improvement and sustainability support requires a shift in current views; an increased focus on back-end data, an increased focus on practices, and the adoption of a life cycle approach. The extension of RDM applications to the back-end, such as customer claims analysis, facilitates front-end improvements in product development. Moreover, adopting a life cycle approach to identify noise factors opens up a wider range of opportunities to involve RDM efforts in product development activities.

Keywords: Robust design methodology, sustainable product development, back-end data, life cycle approach, practices.

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Gothenburg, May 2013
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Siva, V. (2012), Quality Innovation Prosperity, Vol. 16, Iss. 2, pp. 84-103.

Paper II – A Life Cycle Approach to Robust Design Methodology

Siva, V, Gremyr, I, Raharjo, H, Svensson, B. (2013), submitted for consideration of publication.

An earlier version of this paper was presented and published in the Proceedings of the 14^{th} QMOD-ICQSS Conference in San Sebastian, Spain, 29 - 31 August, 2011.

Paper III – A Conceptual Integration of Robust Design Methodology and Sustainability

Gremyr, I, Siva, V, Raharjo, H, Goh, T.N. (2013), submitted for consideration of publication.

An earlier version of this paper was presented and published in the Proceedings of the IIE Asian Conference in Singapore, 28 - 30 June, 2012.

1 Introduction

This chapter contains a general introduction of the research area highlighting the research problem. The purpose of this thesis is then presented, followed by three research questions. The relevance of the problem is discussed along with theoretical and practical implications of addressing the research questions. The chapter ends by outlining the thesis.

In the 1990's, Quality Management (QM) emerged as a concept adopted across industries and in research (Anderson & Rungtusanatham, 1994; Juran, Joseph M, 1995; Juran, J.M. & Godfrey, 1999). Since then, QM has been applied widely in manufacturing industries (Flynn et al., 1995; Terziovski, Milé & Samson, 1999) and service sectors such as healthcare and hospitality (Parasuraman et al., 1985). In subsequent years, QM reached a stage of maturity as a management philosophy characterized by principles, practices and tools (Dean & Bowen, 1994; Sousa, R. & Voss, 2002), where each principle is implemented through a set of practices, which are then supported by a range of tools. Lately, QM has received increased attention in the face of a current challenge in industries; addressing sustainability concerns in the development and manufacturing of products (Wilkinson et al., 2001; Pullman et al., 2009; Smith & Sharicz, 2011; Stocchetti, 2012). One way to address this challenge is to integrate sustainability considerations into existing philosophies and methodologies in industry (Paramanathan et al., 2004; Robinson, 2004; Lubin & Esty, 2010). There is a need to explore opportunities for integration of sustainability considerations into as many existing methodologies as possible, one example being QM (Klassen & McLaughlin, 1993; Angell & Klassen, 1999; Ahmed, N. U., 2001; Foster & Jonker, 2003; McAdam, Rodney & Henderson, 2004).

Within the QM field, a Japanese engineer, Genichi Taguchi, devised a concept called "quality loss". Unlike the traditional definition of quality, Taguchi defined quality loss as *"loss imparted by the product to society from the time the product is shipped"* (Dehnad, 1989) (p. 4). As the word "quality" generally implies a sense of desirability, whereas the word "loss" implies the opposite, the definition was found quite unsettling. The explanation provided by Dehnad (1989) (p. 4) follows:

> *"The essence of his (Taguchi's) words is that the societal loss generated by a product, from the time a product is shipped to the customer, determines its desirability. The smaller the loss, the more desirable is the product. All societal losses due to poor performance of a product should be attributed to the quality of the product."*

Taguchi's depiction of quality loss caused by a product includes the failure to be fit for use, failure to meet ideal performance and harmful side effects caused by the products. The quality loss concept was advocated by Taguchi for the use of "robust design methodology" (RDM) as an approach to reduce quality loss (Phadke, M.S., 1989). The purpose of RDM is to address the challenge of high variability in developing products, as well as producing products at high speed and low cost (Phadke, M.S., 1989). The definition of robustness as stated by Taguchi (Taguchi, G. et al., 2000) (p. 4):

> *"The state where…the product…performance is minimally sensitive to factors causing variability (either in the manufacturing or user's environment) and aging at the lowest unit manufacturing cost."*

Designing products with built-in robustness allows products to be fit for use and to perform at ideal capacity. This in turn ensures that the qualities of products are maintained at a desirable level during their use stage and, therefore, minimizing losses, such as scrap or early life product failures. Taguchi's concern regarding harmful side effects caused by products lacking robustness and quality is appropriate for further elaboration when addressing the need for industries to comply with sustainability considerations in development of products. In today's market, effects caused by products are no longer confined to a single user. In the example of a car, the user is not the only individual affected by the effects of the car. In terms of safety, the communities surrounding the user are affected, and in terms of pollution, the natural environments where the car is driven are affected. Sustainability considerations integrated in the requirements for developing the car, for example, is one way to ensure reduced effect to the communities and natural environments.

Organizations are moving forward in fulfilling their obligation towards contributing to sustainability by expanding their focus from profit-based businesses to also include the sustainability-conscious provision of products and services (Bhamra, 2004). To effectively do so, the short-term and long-term effects of a product need to be considered in the development and design of new and existing products by addressing the demands of sustainability during product development (Johansson, G., 2002; Kleindorfer et al., 2005; Gehin et al., 2008). One way to address this demand is by integrating sustainability considerations into existing design and quality tools and methodologies (Luttropp & Lagerstedt, 2006; Lopes Silva et al., 2012; Remery et al., 2012; Trela et al., 2012).

As a subset of QM, RDM is characterized by principles, practices and tools (Hasenkamp, T. et al., 2009). The main underlying principles of RDM (Arvidsson & Gremyr, 2008) are an awareness of variation and creating insensitivity to noise factors. Another principle is to continuously apply the main principles throughout the product development stages. The emphasis to continuously apply RDM expands the traditional view of RDM as a front-end focused effort. RDM is also applicable at all stages of product development, including the back-end. The front-end refers to the design stages of product development, whereas the back-end refers to the manufacturing or use stages. RDM principles can be applied in all stages of product development through implementation of relevant practices. However, practices throughout product development have not been adequately addressed. There is a need to develop practices to support the continuous applicability of RDM throughout product development (Hasenkamp, T. et al., 2009), in addition to relevant practices to explore the possibility of integrating sustainability considerations into RDM.

1.1 Purpose

The purpose of this thesis is to contribute to the extended application of RDM by using back-end data for front-end improvement and by exploring how RDM might contribute to sustainable product development (SPD).

The extended application of RDM by using back-end data is addressed by research questions (RQ) 1 and 2.

RQ1. Can the use of back-end data be supportive of RDM?

RQ2. How can an analysis of back-end data be supportive of the continuous applicability principle of RDM?

RQ3 addresses the extended application of RDM by exploring how RDM might contribute to SPD.

RQ3. How may RDM efforts contribute to SPD?

1.2 Relevance

This thesis generally relates to the area of QM, specifically RDM as a subset of QM. These approaches are widely related to and practiced in industry. Hence, the relevance leans towards practical applications.

Within QM, there are attempts at framing the QM movement into three generations: the first generation QM between 1930 and 1980; the second generation 1980-2000, and the third generation QM movement from the year 2000 until the present day (Foster & Jonker, 2003; Bergquist et al., 2008). Within the third generation QM, there is a need for adaption to address the connection between organization and society (Bergquist et al., 2008; Garvare, R. & Johansson, 2010). The connection between organization and society is relevant in addressing sustainability concerns such as the impacts of products to society and environment. Sustainability concerns in industries are large and current. Therefore, there is a need for organizations to find ways to address the concerns in as many ways possible, one being integration with QM.

Foster and Jonker (2003) have identified a number of characteristics of each generation of the QM movement, one of which is the criterion for success. The criterions for success are reliability for the first generation, efficiency and effectiveness for the second generation and accountability for the third generation of QM. Accountability suggests that organizations assume responsibility for what they produce. The accountability criterion is relevant to the discussion of widening the definition of customers to include various organizational stakeholders (Klefsjö et al., 2008). Organizations are required to expand their current focus on single customer who uses the products to include other parties who are involved in the life cycle of the products, for example suppliers, environmental groups and policy makers. In short, the third generation QM emphasizes organizational accountability for what they produce to all stakeholders involved. Applying RDM principles to all stages of the product life cycle is one way of underpinning the third generation QM, where stakeholders are affected by one life cycle stage or another. Also, aligning RDM efforts according to their contribution to SPD by using a life cycle approach represents a step forward in widening the view of customers to include those *"affected by the product throughout its life cycle"* (ibid., p. 125).

1.3 Implications

In previous RDM research, the focus has been on tools for robust design and their applications (Roy, 1990; Shoemaker et al., 1991; Myers et al., 1992; Andersson, 1996; Goh, 2002). The "Design of Experiments" (DoE), for example, has been widely advocated as an important tool to be applied at the early stages of product development (Box & Meyer, 1986). However, through practices of RDM, industrial practitioners i.e. engineers, designers and managers have more opportunities to understand and address variation in product performances. Focusing on practices, RDM can be continuously applied, not only throughout product development, but also throughout the life cycle of a product. A practice suggested is the analysis of back-end data based on the product life cycle approach to identify noise factors at all stages of the life cycle. Further, adopting a life cycle approach in relation to RDM principles and practices represents an addition to the theoretical advances previously made.

The integration of sustainability considerations into product development has been receiving increased attention in both research and practice (McAloone, 2000; Kaebernick et al., 2003; Griese et al., 2005). The attention has been mainly paid to environmental sustainability considerations in product design and development, as well as to manufacturing (Bovea, M. D. & Vidal, 2004; Dewulf & Duflou, 2005; Kobayashi, 2006; Yang, Q. & Song, 2006; Ben-Gal et al., 2008; Cerdan et al., 2009). In the efforts towards SPD, economic and social sustainability considerations have not been extensively addressed alongside environmental sustainability. A life cycle approach to analyze customer claims suggested as an RDM practice may facilitate identification of more causes of variation. This approach would create an opportunity to avoid failures, leading to possible reductions in customer claims and the waste of resources through scraps. Also, the integration of sustainability considerations into product development tools such as QFD (Masui et al., 2003) and the Kano model (Sakao, 2009) are examples focused on environmental sustainability implications. The same focus is pointed out as an area for future research with regards to RDM tools (Ben-Gal et al., 2008; ten Napel et al., 2011).

1.4 Thesis Structure

The structure of the rest of the thesis is as follows:

Chapter 2 presents the theoretical background on which the research is based, namely QM, RDM, and SPD, followed by an elaboration on the noise factors of RDM and the application of back-end data in product development. Chapter 3 presents the research methodology, including the research process and approach, research design, data collection and analysis methods, ending with a note on the trustworthiness of the research. Chapter 4 summarizes three appended papers, the core of this thesis, followed by a discussion of a number of common themes identified in all three papers. In Chapter 5, a general discussion of the thesis is presented, followed by the conclusion in Chapter 6. Finally, Chapter 7 contains ideas for the future direction of this research. These Chapters are followed by a Reference List, and Appended Papers I, II and III.

2 Theoretical Background

This chapter presents the theoretical background related to the research area and problem, namely QM and its ties to sustainability, RDM and SPD. Further, the application of back-end data for continuous improvement and adoption of the life cycle approach are presented to create a better understanding of the practices identified in this thesis.

2.1 Quality Management towards Sustainability

The definition of QM has been anything but constant since its conception. QM evolved from quality inspection at the end of a production line to an all-encompassing management philosophy in the 1990's (Anderson & Rungtusanatham, 1994; Powell, 1995; Lengnick-Hall, 1996; Martinez-Lorente et al., 1998) characterized by its principles, practices and tools (Dean & Bowen, 1994). The principles of QM are in line with organizational development such as systematic problem solving, cross-functional integration and continuous improvement, to name a few aspects (Dahlgaard, 1999). Over the last decade, when a shift in the focus from tools and techniques to QM practices was witnessed, successful QM practices resulted in a number of advantages to organizations, including increased organizational performance (Sousa, R. & Voss, 2002; Nair, 2006), enhanced customer satisfaction and productivity (Terziovski, M., 2006), improved project management (Bryde & Robinson, 2007), and better quality performance (Zu, 2009).

The principles of QM continued to evolve, taking a turn towards supporting the environmental performance of organizations, e.g. the ISO 14000 Environmental Management System (Kitazawa & Sarkis, 2000; Theyel, 2000). This trend was followed by a discussion of the commitment of an organization to the community in which it exists, i.e. corporate social responsibility (CSR) in the context of QM (McAdam, R. & Leonard, 2003). It was claimed that *"CSR has a strong affinity with the principles of quality management"* in terms of business ethics (ibid., p. 36). Others suggested using quality excellence models as bases for CSR assessments in organizations in order to fulfill the needs of various stakeholders (Kok et al., 2001).

An extended quality excellence model integrated with sustainability considerations was proposed to balance organizational processes against economic, social and environmental concerns (Garvare, Rickard & Isaksson, 2001). The authors argue that such a model is needed to measure organizational performance in terms of sustainability excellence through the use of QM practices. For example, quality improvement initiatives, such as Six Sigma, resulted in enhanced customer satisfaction and increased profit, as well as the continuous improvement of environmental performance based on ISO 14000. Further, one QM practice, namely the measurement of the 'cost of poor quality' was used as an indicator of economic sustainability exemplified in the case of a cement factory (Isaksson, 2005). The example of the cost of poor quality according to Isaksson (2005) includes costs incurred to customers and the loss of income to the organization due to low quality cement. Such losses indicate involvements of various organizational stakeholders, including end-users, building constructors, and suppliers. The management of these stakeholders become a critical concern for the discussion of organizational and global sustainability (Garvare, R. & Johansson, 2010). The management of stakeholders and their values are viewed as indicative of the future direction of QM (Foster & Jonker, 2003; Zink, 2007).

Stakeholders comprise people and organizations whose input is vital to the continuing existence and prosperity of a business. Of all QM practices, customer-focused practices are identified as the most critical and distinctive (Sousa, Rui, 2003), centering on the notion that the customer is viewed as a major stakeholder in the area of QM (Klefsjö et al., 2008). Some authors suggest replacing the word "customers" with "stakeholders" to address the connection between organizations and society for the continued evolution of QM (Bergquist et al., 2008; Garvare, R. & Johansson, 2010). Such step could be viewed as a way of embracing the integration of sustainability considerations into existing methodologies such as QM (Klassen & McLaughlin, 1993; Angell & Klassen, 1999; Ahmed, N. U., 2001; McAdam, Rodney & Henderson, 2004; Rusinko, 2005).

Klassen and McLaughlin (1993) state that *"environmental excellence also begins during initial product and process design"* (p. 19). Angell and Klassen (1999) argue that performance might be enhanced by including environmental criteria in quality methodologies. The authors identified that the lack of integration of environmental criteria in design tools was a significant hurdle. Considering these arguments, the integration of sustainability considerations into QM is not limited to principles, such as customer focused and continuous improvement principles. The integration of sustainability considerations is also necessary in QM tools, specifically design tools used to produce robust products (Klassen & McLaughlin, 1993). Within QM, RDM is a methodology containing such design tools.

2.2 Robust Design Methodology

RDM is defined as *"systematic efforts to achieve insensitivity to noise factors, founded on an awareness of variation and can be applied in all stages of product design"* (Arvidsson & Gremyr, 2008) (p. 31). The definition is based upon the three underlying principles of RDM; an awareness of variation, creating an insensitivity to noise factors, and the continuous applicability of RDM throughout all stages of product design. Hasenkamp et al., (2009) proceeded to adding to these RDM principles by identifying related practices and tools to support these practices.

The application of tools and techniques, such as DoE and the Taguchi method, has been the common research focus within RDM in the recent past (Gu et al., 2004; Wu, D. H. & Chang, 2004; Kovach & Cho, 2006; Lee & Park, 2006; Beyer & Sendhoff, 2007; Besseris, 2010; Yadav et al., 2010). However, research focused on RDM principles (Arvidsson & Gremyr, 2008) as well as practices (Hasenkamp, T. et al., 2009) has been scarce. In addition to tools and techniques, RDM is also characterized by its principles and practices. Lifting the focus from tools to efforts centered on the underlying principles of RDM creates novel opportunities to extend the application of RDM, specifically in contributing to the growth of RDM practices (Hasenkamp, Torben, 2009; Cabello et al., 2012).

RDM is commonly described as an approach to reduce performance variation in products and processes (Shoemaker et al., 1991; Andersson, 1996; Goh, 2002). Performance variations are caused by the presence of various factors both within the manufacturing environment and beyond. Robustness of products are achieved by managing the factors causing variability, also known as noise factors (Kackar, 1985; Taguchi, G., 1986; Phadke, M.S., 1989). Noise factors during the manufacturing stage due to regulated space, are, to a large extent, easily realized, e.g. a production line, clean room manufacturing, and an automated assembly line. The same does not apply to noise factors that may exist in user environments, where products are exposed to a variety of external conditions, such as temperature and humidity and the handling of products by various users (Johansson, P. et al., 2006).

2.2.1 Noise Factors

A concept to visualize a product within RDM is a block diagram called a "P-diagram", where P stands for 'product/process' (Phadke, M. & Dehnad, 1988) as shown in Figure 1. Control factors are controllable design parameters used to optimize the performance of the system, ideally producing the desired optimal output. Noise factors are parameters caused by any sources of variation that cannot be controlled (Phadke, M. & Dehnad, 1988; Phadke, M.S., 1989).

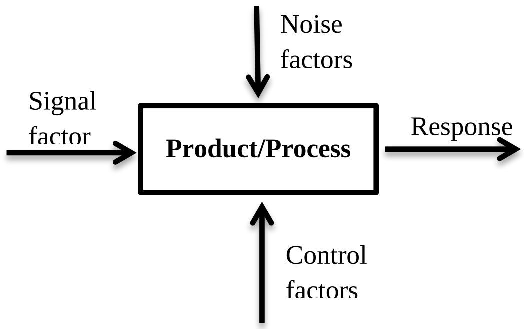

Figure 1: P-diagram

Noise factors which result in variations of product performance are traditionally categorized as: (1) environmental variables (external sources), (2) product deterioration (internal sources) and (3) manufacturing imperfections (internal sources) (Phadke, M.S., 1989; Taguchi, G., 1993). Examples of environmental variables are temperature conditions, dust, and vibrations. Product deterioration is seen in examples of wear and tear and the degradation of components over time during usage. Manufacturing imperfections, on the other hand, are seen in unit-to-unit variations of products due to manufacturing process variations (Mekki, 2006; Johannesson et al., 2012).

The use of cars in extreme weather conditions of +40 degrees C and -20 degrees C may result in cracked paint in African cars and frozen car batteries in Swedish cars. Common spare parts subject to deterioration include tires and brake pads that wear off over time. As car manufacturing nowadays is widely modularized and automated, unit-to-unit variation may diminish. Nevertheless, due to missed preventive maintenance of paint cleaning tanks in car paint spray-booths, colors may vary from one batch of cars to another.

The off-line and on-line quality control methods were introduced as ways to manage or control the influence of noise factors (Taguchi, G, 1978). Noise factors could be addressed through countermeasures at three different stages of product development, i.e. product design, process design and manufacturing (Kackar, 1985). Off-line quality controls are applicable only during the product design stage as countermeasures to environmental variables and product deterioration, whereas on-line quality controls are applicable to all stages of product development as countermeasures to manufacturing imperfections alone which is shown in Table 1, where X indicates areas where countermeasures against noise factors are not possible.

Table 1: Product development stages and quality control methods, adapted from Kackar (1985)

Stages of product development	Sources of variation		
	Environmental variables	Product deterioration	Manufacturing imperfections
Product design	Off-line controls possible	Off-line controls possible	On-line controls possible
Process design	X	X	On-line controls possible
Manufacturing	X	X	On-line controls possible

According to Taguchi (1978), to effectively create robustness, efforts to manage noise factors are desirable already during the design phase of product development. Back-end efforts, i.e. process design and manufacturing stages (see Table 1), are arguably futile in an attempt to create robustness against environmental variables and product deterioration. Managing sources of variation has commonly been emphasized in early design phases of product development, i.e. front-end efforts (Andersson, 1997; Celik & Burnak, 1998). The need to address the sources of variation during the conceptual phase as front-end efforts has been pointed out by many authors (Kackar, 1985; Andersson, 1996; Thornton, 2004; Nepal et al., 2006; Hasenkamp, Torben, 2009; Cabello et al., 2012). However, the lack of practices to address the continuous applicability of RDM (Hasenkamp, T. et al., 2009) to all stages of product development limits the possibilities for front-end efforts.

Looking at the current RDM focus centered on tools such as DoE, practices are often limited to the specificity of the tool (Montgomery, 1999). DoE has its merits as a tool in analyzing influences of control factors and possible noise factors in the system suitable for front-end application (Phadke, Madhav S, 1988; Roy, 1990). However, focusing on tools alone is arguably insufficient in addressing the need for additional front-end efforts. The use of DoE at early design stages requires designers to have detailed knowledge of the characteristics of the concept, in addition to some statistical skills related to DoE, which limits the applicability of RDM in early design stages with less detailed specification of the products. Back-end practices are needed to continuously apply RDM, whereas those involved in back-end activities, such as manufacturing and distribution, need to be trained to think in terms of variation and noise factors in their own processes. This fact, in turn, creates an opportunity for additional front-end RDM efforts by using data on variation and noise factors from, for example, manufacturing and distribution.

2.3 Application of Back-End Data

In QM, a key area of focus for quality improvement efforts is the design or front-end phase of product development (Kumar, V. et al., 2012). The focus on improvement efforts at the front-end have resulted in initiatives such as Design for Six Sigma (Chowdhury, 2005), and tools such as the Kano model (Tontini, 2007) and Quality Function Deployment (QFD) (Ficalora & Cohen, 2009), to name a few. Customer involvement in the product design stage is a main attribute of tools such as QFD and the Kano model that contribute to the application of QM at the front-end of product development. These front-end efforts have been contributing to the improvement of product design to fulfill customer needs and expectations (Tan & Shen, 2000; Cristiano, J. J. et al., 2001; Chan & Wu, 2002; Akao & Mazur, 2003).

However, an area of interest and opportunity that has not been widely explored is the back-end of product development. Information regarding customer needs and expectations are typically in focus for development efforts, where techniques such as focus groups and interviews of new customers are employed (Cristiano, John J et al., 2000). According to Cristiano et al. (2000), another source of information for product development comes from existing customers in the form of complaint information and warranty data. The authors state (ibid., p. 305):

> *"…to focus on complaint and warranty information implies a basic understanding of customer needs and is consistent with a continuous improvement strategy for product development – fixing problems with the current product and incrementally improving."*

Back-end data, such as customer complaints and warranty information, is *"a prime source of field reliability data"* to be utilized for such examples as, *"constructing a database of failure modes and their relation to the environmental conditions and how the product is used."* (Karim & Suzuki, 2005)

(p. 668). Warranty data containing information on failures, such as the point in time during product usage when the failure occurred, is connected to product reliability improvement (Ahmed, J. U., 1996), where reliability is a key concern in ensuring customer satisfaction and field data can be used to *"find out what you don't know about reliability"*(Doganaksoy et al., 2000) (p. 121). Ahmed (1996) argues that the reliability of product is strongly influenced by efforts made during the design stage and suggests RDM as an appropriate approach to reliability assurance by using the Failure Mode and Effects Analysis (FMEA) and DoE. Besseris (2010) has presented a methodology using DoE as one component of creating an optimization technique for reliability improvement, illustrated by a case study. Further, Besseris (2010) argues that *"among the most popular approaches that aid in boosting reliability in manufactured products has been channeled through design of experiments (DoE)"* (p. 742).

Another piece of relevant information usually found in warranty data is "failure mode", where it is argued that *"analysis by failure modes are useful for product reliability evaluation and improvement"* (Doganaksoy et al., 2002) (p. 52). Others have applied warranty data as a way of addressing design improvement, where the information flow from the field to the design stage is called a feedback loop (Magniez et al., 2009), creating opportunities to tackle unanticipated failure modes (Wu, H. & Meeker, 2002; Meeker & Escobar, 2004). Further, the use of warranty data has been suggested as a way of practicing the QM principle of continuous improvement in organizations (Blischke et al., 2011). Further, Magniez et al., (2009) illustrate the use of RDM as an approach to design improvement, where failure modes are replicated in experiments at the design level. As the failure is no longer unanticipated, the characteristics that drive the failure mechanism may now be measured. Product design improvement is then possible when the design parameters involved in the failure mechanism are identified and the recurrence of failure through design modification avoided.

In most organizations, the shortage of customer complaints data and warranty information is not a problem (Wu, H. & Meeker, 2002; Fundin, A. P. & Cronemyr, 2003). However, organizations face challenges on deciding how to utilize the data to be supportive of continuous improvement efforts (Fundin, A. P. & Bergman, 2003; Fundin, A. & Elg, 2010). Other challenges in utilizing customer complaints include a lack of a structured and systematic way of analyzing the data for improvement purposes, and the failure to realize the benefits that may arise by analyzing complaints (Zairi, 2000).

2.4 Sustainable Product Development

Aligned with sustainable development initiatives, sustainability considerations have been interspersed in the development and manufacturing of products (Senge et al., 2001; Wilkinson et al., 2001; Anastas & Zimmerman, 2007; Nidumolu et al., 2009). Early efforts to raise sustainability considerations focused on product end-of-life strategies such as creating proper product disposal methods, increasing the availability of recycling options, controlling the hazardous waste of after-production and emissions from the disposal of products (Sarkis, 1995; Boks & Tempelman, 1998; Linton, 1999; Chiodo & Boks, 2002). From these early efforts of end-of-life initiatives and measures, sustainability considerations have moved upstream to the design stages of products (Johansson, G., 2002; Sun et al., 2003; Bhamra, 2004; Kleindorfer et al., 2005; Azapagic et al., 2006; Gehin et al., 2008).

In order to address the sustainability considerations effectively at the design stages, there is a need for integration of these considerations into existing tools and methodologies (McAloone, 2000; Kaebernick et al., 2003; Masui et al., 2003; Berchicci & Bodewes, 2005; Griese et al., 2005; Sakao, 2009). Further, SPD based on the cradle-to-grave approach was seen as an initiative of transitioning the focus from product end-of-life sustainability impacts, such as recycle and reuse, to reduced impacts across the life cycle of a product (Rydberg, 1995; Hanssen, 1999; Ljungberg, 2007; Gehin et al., 2008). As far as SPD is concerned, three main ideas could be summarized based on literature. One, sustainability considerations need to be made early in the product design stages. Two, a way to do so is by the integration of sustainability considerations into existing tools, and three, the adoption of a systems approach based on a product life cycle view is necessary.

2.4.1 Early Considerations

In product development, design considerations should be included as early as possible to avoid detecting problems at the back-end, i.e. manufacturing stage, as they become increasingly costly to correct. According to Gehin et al., (2008), the problems of adopting sustainability considerations early in product development is not due to a lack of tools to help designers make optimal design decisions, but rather that the tools fit poorly into the existing product development process because of rigid product development processes, the lack of flexibility to adapt to more than one specific product, and the lack of tool integration in design activity.

Trela et al. (2012) state that, in addition to technological and market demands, product development in industry is also affected by sustainability considerations. A challenge identified in connection with this demand is the lack of knowledge on how to integrate sustainability considerations at the early stage of product design. An approach taken in a case study by Trela et al., (2012) is adapting existing processes and tools to tackle the sustainability considerations effectively during the early stages of product design. The authors propose a model, derived from a conventional product design process, that consists of existing tools and processes such as product typology, a flow study, functional analysis, and pre-assessments. Tools and processes were adapted to include sustainability considerations for the product in the case study, a hybrid-heating appliance. Early strategic decisions based on adapted tools and processes are important to address sustainability considerations in the development of new products.

Remery et al., (2012) present a method to evaluate and select end-of-life options before the beginning of the detailed design stage. The authors propose a new end-of-life scenario evaluation model, where an evaluation method is applied early during the product design stage to optimize the design for the environmentally sustainable end-of-life scenario. The proposed model was based on a multi-criteria decision method, where end-of-life options such as recycling, remanufacturing, or disposal were individually ranked and selected. The use of the model was illustrated by means of a case study to design a vehicle engine. It was suggested that considerations of end-of-life options early in the product design stage presented a sustainability potential that was visible in back-end activities in the case of remanufacturing, leading to less manufacturing waste.

2.4.2 Integration into Existing Tools

According to Lopes Silva et al., (2012) in their study of Cleaner Production, there are three main barriers to the implementation of sustainability initiatives in organizations: a lack of integration and systematic implementation, a lack of continuity and a resistance to change. When sustainability considerations are left as stand-alones outside the design process, greater efforts are required from designers and engineers in learning and implementing these initiatives. On the other hand, when these considerations are included as a requirement integrated into an existing tool, for example product weight monitoring on a control chart, implementation presumably becomes easier and the integration becomes more natural.

The integration of sustainability considerations into existing tools and practices was also found necessary to promote ownership and responsibility among employees in an organization (Tingström et al., 2006). An integrated approach creates room for those involved in product development to directly take ownership of sustainability considerations with regard to product development. Members of development projects are, in terms of product knowledge, more suited to making design decisions than external environmental experts hired to assist in projects on a short-term basis, an argument in line with the findings of Lopes Silva et al. (2012).

Bhamra (2004) states that the integration of sustainability considerations into existing design tools is necessary for *"balancing it with other design considerations such as cost, quality and functionality"* (p. 558). Similar statements were made based on a literature review related to research on SPD (Baumann, H. et al., 2002). There are two important lessons learned from this statement. The first lesson is that sustainability considerations are no longer optional, or merely a sideline activity, for organizations. As cost, quality and functionality of products are developed, these requirements must be considered equally. This could be traced back to environmental regulations imposed on organizations by policy makers, one type of stakeholder. Also, end customers, another type of stakeholder, who are increasingly aware and responsible, may impose on organizations to produce environmentally-conscious products.

The second message is that possible trade-offs between these requirements become easier to identify and tackle when the considerations are made at early design stages (Byggeth & Hochschorner, 2006). For example, a sustainability consideration leading to change of current raw materials, the effect of such decisions on the purchasing cost of the material and the cost of manufacturing process changes need to be confronted early in the product development phase. Sustainability considerations during product development may not always be linked to increased costs (Willems & Stevels, 1995; Camahan & Thurston, 1998). In the case where sustainability considerations in the early stages of the product development lead to increased costs, there is a likelihood that the investment pays off at a later stage owing to, for example, increased sales or efficient disposal (Christmann, 2000; Zhu & Sarkis, 2004; Bovea, M. & Wang, 2007).

Ben-Gal et al. (2008) demonstrated the use of the RDM tool to arrive at a suitable design for a factory smokestack that emits sulfur dioxide. Experiments were conducted using control factors and noise factors. The study showed that RDM was suitable to design a smokestack that minimized the emission of air pollutants, and therefore contributed positively to the environment. This study successfully applied the method where optimal output was based on a predefined target value, with the experiments helping designers find the right settings of control factors and noise factors to achieve the target value. However, the underlying principles of RDM or the practices supporting these principles were neither addressed nor discussed which further supported the current trend of RDM research, where the focus is largely on tools such as DoE and its applications. In the case presented by Ben-Gal et al. (2008), using emissions of a non-friendly substance as outputs, the effect on the environment was directly controlled by using DoE. The same may not apply in other cases where the output is not directly related to the environment. The application of DoE in the case of the factory smokestack is not in question but the reference to the smokestack study implies that there is a need to shift the focus from tools such as DoE to the principles and practices of RDM to identify other possible connections to the sustainability benefits.

2.4.3 Life Cycle Approach

In the cradle-to-grave approach, a product life cycle refers to the product stages *"followed from its 'cradle' where raw materials are extracted from natural resources through production and use to its 'grave'"* (Baumann, Henrikke & Tillman, 2004) (p. 19). Another approach of SPD, cradle-to-cradle, further discusses designing of products within a design framework that turns the materials into substances which are biologically degradable at the end of use, or recovered and reused in the creation of new products (Braungart et al., 2007; McDonough, W. & Braungart, 2010). The materials used in the design and manufacture of products are returned to its original state in what is called a closed-loop cycle (McDonough, William et al., 2003).

Because of the reasoning that reducing environmental impacts in only one stage while ignoring others may result in negative contributions to sustainability (Klöpffer, 2003), a systems approach is considered necessary. An engine component of a car may be selected due to the weight and durability of its raw material, contributing to sustainability in terms of low fuel consumption. On the other hand, the disposal of the particular material may be hazardous to the environment at the end-of-life stage, which indicates that considerations made at one stage of a product life cycle may result in negative contributions at another stage. Klöpffer (2003) further adds that *"...a systems approach has to be taken. Only in this way, trade-offs can be recognized and avoided. Life cycle thinking is the prerequisite of any sound sustainability assessment"* (p. 134).

Kaebernick et al., (2003) argue that *"the introduction of environmental requirements into the product development process at all stages of a product's life leads to a new paradigm of sustainability, which is reflected in a new way of thinking, new application of tools and methodologies in every single step of product development"* (p. 468). This argument indicates that sustainability considerations in product development require a life cycle approach encompassing all stages of products from design to manufacture, usage and end-of-life. Azapagic et al., (2006) state that integration of sustainability considerations into product development requires a systems approach by taking both front-end and back-end activities into account. For example, designing the manufacturing process requires considerations of the front-end origin, such as raw material selection, and the back-end destination, such as end-of-life options.

Common stages of a product life cycle consist of raw material, manufacturing, distribution, product use, and end-of-life (Choi et al., 2008). Table 2 shows the common product life cycle stages and some examples of specific strategies concerning sustainability considerations, adapted from Choi et al., (2008).

Table 2: Life cycle stages and strategies adapted from Choi et al., (2008)

Life cycle stages	**Strategies**
Raw material	Reduction of material use Use of recycling and recyclable material Avoid toxic or hazardous substances
Manufacturing	Avoid waste of material Clean production Minimized variety of material
Distribution	Reduced weight of product Reduced weight of packaging Re-use and recyclable packaging
Product use	Avoidance of waste Product durability Product efficiency
End-of-life	Re-use and recycling Remanufacturing Safe disposal

3 Research Methodology

This chapter presents the methodological choices made in addressing the research questions. It begins with a description of the research process and the approach accounting for the motivations of the ensuing research design. Then, data collection methods and analysis are discussed according to the sequence of the research questions. The chapter ends with discussion of the trustworthiness of the research.

3.1 Research Process and Approach

The research process began in January 2011 as an initiative of the Production Area of Advance at Chalmers. The Sustainable Production Initiative (SPI) has RDM as a major area of interest. The aim of the Production Area of Advance is to explore new ways to achieve industrial competitiveness and resource efficient product and production development processes. Sustainable Product Development is a research area within SPI that focuses on product development methods and tools.

QM, and RDM as a subset within it, originated as a consequence of practical experience. Some quality leaders, founders of quality tools, and advocates of approaches such as Six Sigma or Lean Production have been industry practitioners. Engineers in various organizations bear names such as Walter Shewhart, founder of Statistical Quality Control, Edward Deming, creator of the Plan-Do-Check-Act cycle, Joseph Juran, author of the Quality Control Handbook, Shigeo Shingo, founder of the just-in-time concept, and Bill Smith of Motorola, founder of Six Sigma. These names also include Genichi Taguchi, the founder of robust design, who was at the time an engineer at a Nippon Telephone and Telegraph Company laboratory in Japan (Chapman, 2009; Kumar, S., (n.d.)). The quality concept lives on in practices that apply various quality tools and methodologies to real-life settings (Wu, Y. & Wu, 2000; Adams et al., 2003; Womack et al., 2007; Oakland, 2012). The attempt to explore and understand such practices calls for a research design involving practitioners, emphasizing the need to establish collaboration with industry.

The first collaboration with industry on this thesis was established in early 2011 with a medium-size Swedish manufacturer that evidenced a growing interest in the area of robust design As a result, the organization voluntarily expressed its interest in taking part in this research. The term “convenience sampling” naturally comes to mind. One of the common problems in conducting research involves issues of access to relevant and required data (Karlsson, 2008). The voluntary involvement of the organization resolved this difficulty from the start. As suggested and advocated by some authors (Patton, 2002; Maxwell, 2005; Weiss, 2008), such a collaboration could also be classified as “purposeful sampling”. Purposeful sampling refers to a particular setting where one could attain required information that may not be available through random samples (Maxwell, 2005). The organization’s setting was found to be purposefully fitting overall initial requirements of this research.

3.2 Empirical Setting

The “empirical setting” is a manufacturing organization where QM is adopted and practiced. It has a functional product development (PD) process driven by a cross-functional team representing Production, Purchasing, Research & Development, Quality, and Marketing personnel. The PD team works actively using quality tools like FMEA in developing new and existing products, while emphasizing the latter. The organization is an automotive component manufacturer whose products are known for their reliability in terms of functioning and safety due to the extreme and variable conditions in which they are used and a lengthy product life cycle that may last 15 years. The organization exercises its goals to be customer-focused and continuously improve products and processes with a seriousness of purpose, especially with regard to reliability issues. RDM was viewed as an approach by which the organization's product quality issues could be addressed. Further, with the availability of datasets in its customer claims system, the organization was keen on identifying new practices to enhance the effective management of its claims process and usage of claims data. The collaboration with shared purposes was, therefore, off to a good start and is currently ongoing.

Researching practices in real-life settings was an approach by which to address the research purpose. Another approach, specifically for Research Question 3, was to establish a connection at a conceptual level between RDM and SPD. The conceptual integration of RDM and SPD was accomplished based on previous research in the field, as well as illustrative case studies of RDM from the literature.

3.3 Research Design

During the decision-making process concerning the research design of this thesis, certain basic research criteria were considered. The types of research questions addressed to fulfill the research purpose form a basic criterion. Other criteria include the role of theories, the relationship between theory and data, the levels of analysis, philosophical standpoints assumed in the conduct of research, and the trustworthiness of the research findings (Karlsson, 2008). These criteria will be further explained to support the choices made with regard to the research design.

Research questions serve several purposes during the research process and are typically raised to address a perceived problem within a certain research field. Deciding on different designs depends on how the questions are posed (Vogt et al., 2012). The purpose of this thesis is to contribute to an extended application of RDM the anticipated results of which are not in the forms of preferences or choices, but rather clarification and explanation (Voss et al., 2002). Interviews are suitable to achieve these purposes.

Previous research within this framework was used as a basis for further investigation and development. For example, the application of RDM principles to claims data analysis is an example of the use of existing theory for further development, opening up opportunities for existing theory to unfold in an exploratory manner. Such exploratory nature requires a back-and-forth movement between theory and data known as an "abductive process", or "systematic combining" (Dubois & Gadde, 2002). In the theory-data relationship, data collection is conducted with prior theoretical knowledge as a basis, resulting in matching theory to data. A refined theory is then suggested with the research design moving between induction and deduction.

The abduction process contributes to theory refinement or development for which a case study is appropriate as a research design (Dooley, 2002; Voss et al., 2002). A focus of this research was on the organizational practices relating to an extended application of RDM that points to the level of analysis. The philosophical position portrayed in the way the research is conducted points to interpretivism, where knowledge is derived from an understanding based on interpretations (Karlsson, 2008).

3.4 Data Collection and Analysis

Various data collection methods were utilized during the course of this research. These methods are described and discussed based on the order of the research questions. There is an overlap between data collection methods for RQs 1 and 2, where data from interviews with the customer claims personnel were used for both studies. Interview data from the PD personnel were specifically used in the study addressing RQ1 where a combination of qualitative data collection and quantitative data analysis methods was applied.

Initially, the case study in Paper I address RQ1 by inquiring whether the use of back-end data can be supportive of RDM. Next, the case study in Paper II addresses RQ2; how can the analysis of back-end data be supportive of the continuous applicability principle of RDM? Lastly, Paper III presents a conceptual study to address RQ3; how may RDM efforts contribute to SPD? A summary of the research design and methods applied is presented in Table 3.

Table 3: Summary of research design and data collection methods

Purpose	Research design	Main data collection method
To suggest practices for application of back-end data, such as customer claims, to support a front-end RDM approach	Case study (Paper I)	Interview Internal document and database Participant observation Affinity exercise
To suggest an analysis of back-end data, such as customer claims, based on a product life cycle approach to identify noise factors in all stages of a life cycle	Case study (Paper II)	Interview Internal document and database Participant observation
To explore how RDM efforts may contribute to sustainability and more specifically SPD	Conceptual study (Paper III)	Literature review

RQ 1: Can the use of back-end data be supportive of RDM?

The empirical setting was provided by the business organization that provided access in terms of employees, products, processes and internal systems such as its customer claims database and PD process. The first step taken to answer the research question was to understand the current use of back-end data at the organization in relation to its product development team and process.

Interviews were conducted with six employees using semi-structured questions. The interviewees are those involved in customer claims and product development processes and included engineers and managers from the departments of Project Management, Quality, Operations, Research & Development, and Human Resources. Each interview lasted between 45 to 90 minutes and was recorded and transcribed. All interviews were conducted in English. The interview questions included such examples as “How useful is the customer claims system to you?” and “Do you consider product failures from the claims system in designing a product?” The semi-structured questions allowed vast pieces of information to be shared and discussed between interviewer and interviewees which created a valuable in-depth understanding of the claims and PD processes and the challenges associated therewith (Flick, 2009).

Internal documents were analyzed to supplement the information gathered through the interviews. The documents encompassed the internal customer claims database, the PD process flow and the product update proposal and quality tool templates, in addition to monthly reports generated from the claims system.

Observations of the customer claims handling process contributed to an understanding of how the claims system operated by spending four to five hours with the two employees in charge of handling these claims. These employees explained and demonstrated the process, starting when the claims were received via claims reports from customers, entering the data into the claims system, following up on existing claims. Such claims could involve other departments, for example, Operations or Research & Development, on actions required to solve the problems contributing to the claims and deciding on outcomes in terms of product replacement or the issuance of invoices to the customers involved.

Further, a batch of products returned by customers in various defective conditions was inspected by the researcher to assist the engineer in charge of defective product returns. The inspection consisted of dismantling 85 units of products, the measurement and recording of defects of products and their components, and segregating these components into disposal bins.

Finally, an affinity exercise was conducted with two employees involved in the claims system and process handling. An affinity exercise involves gathering participant thoughts and ideas in the form of short answers on Post-It notes, and then compiling them based on themes identified in the answers. Affinity exercises contribute to the compilation of unstructured verbal information (Scupin, 1997). This exercise involved the researcher and two Master's thesis students at the organization and was conducted to address the question "What are the major problems in using claims data for improvements?"

The data analysis was conducted in qualitative manner. Recorded and transcribed interviews were analyzed by creating themes based on the information gathered (Thomas, 2006). The interview texts were read to capture and identify themes. The themes identified by the customer claims system included current practices, challenges, data dissemination, data usefulness, and improvement needs.

RQ 2: How can an analysis of back-end data be supportive of the Continuous Applicability Principle of RDM?

Similar to Research Question 1, semi-structured interviews were used as the primary data collection method. The aim was to understand the functions of the customer claims database in Microsoft Access. The questions were mainly formulated to gain insights into the claims database in terms of inputs, data entry process and frequency, claims authorization, information sharing and claims report generation, claims data updates and database maintenance.

Based on their involvement in the claims process and system, two main interviewees were selected, one from the Quality Department, the other from the Sales Department. Both were responsible for the data entry of claims reports into the claims database for two different customer segments. Examples of questions posed to the interviewees: How often are claims data entered into the system? Who else has access to the claims database? What actions do you take in order to close a claims report? What types of reports are generated by the claims system? These interview sessions took between three to four hours each. Observations on how the claims database was handled by these employees were more time consuming than the interviews. Additionally, access to the claims database was made available. The database was explored by browsing through the lists of customers and failure codes, various claims reports, and other reports generated through the database. The two interviewees were asked follow-up questions regarding the claims system, as and when deemed necessary and made possible as the researcher spent full workdays at the facility during each visit.

When the need arose to collect additional information on current challenges in using the claims system and possible ways in which claims data could be used to serve a larger purpose within the organization, another interviewee, the Manager of the Quality Department, was included. This interviewee was the manager of the Quality Department to whom one of the first two interviewees reported. The questions posed to the Quality Manager included: How does your department handle a claim? How do you categorize the failures identified: in the claims reports? What are the actions taken to address a quality defect raised in a claim?

Several meetings were held with the main contact person at the organization, an engineer responsible for product and process improvement initiatives, to gain an in-depth understanding of the products and related failure modes. These meetings lasted between two and three hours each during four workday visits. All interviews and meetings were conducted in English. Interviews were recorded and transcribed and notes taken during the interviews (Yin, 2009). The information from the interviews was used to draw up a flow chart of the claims process with the various failure modes in existence in the organization.

The claims data were extracted from the Access database and imported to the JMP software for quantitative analysis. An Exploratory Data Analysis (EDA) (de Mast, J. & Kemper, 2009) was used to analyze the customer claims data between 2005 and 2010 by using JMP. EDA was introduced by John Tukey (Tukey, 1962) as an exploratory way of understanding the story behind the data and was applied to arrive at a systematic way of analyzing a large amount of claims data. The goal of EDA is to discover data patterns through 'listening' to the data in as many ways as possible until a plausible 'story' becomes apparent (Behrens, 1997). This goal was found suitable in analyzing the claims data for which graphical representations of the data could result in the appearance of a certain visibility (de Mast, Jeroen & Bergman, 2006), for example, the customer with highest number of claims between 2005 and 2010, the product that received the most claims over five years, etc. which was accomplished by displaying data distributions with the help of histograms in JMP.

Similarly, the histograms were also used to list the failure modes of claims, from highest to lowest over the same duration. The failure modes, based on high occurrence, were then categorized according to the life cycle stages of products, i.e. raw material, manufacturing, distribution, usage and end-of-life based on an investigation of the failure modes identifying the stages where the failure may have occurred. For example, when a product was returned due to rusty parts, the failure occurred at the usage stage of the product life cycle. The cause of the failure could be related to parts being exposed to rain water or to the lack of preventive maintenance by the user. The EDA analysis was carried out by two researchers and was validated by the main contact person at the company. Further validation was conducted by an external researcher who was credited with knowledge of RDM (Eisenhardt, 1989).

RQ 3: How may RDM efforts contribute to Sustainable Product Development (SPD)?

A conceptual model was used to integrate RDM and SPD theoretically. This integration was accomplished by reviewing previous research on these topics, identifying the common themes between them and differentiating between the contrasts (Meredith, 1993), followed by suggestions for a future research agenda. The conceptual integration was based on four general conceptual goals, namely envisioning, explicating, relating and debating (MacInnis, 2011). The underlying theoretical ideas of RDM and SPD were reviewed supported by secondary data from published case studies on robust design. The aim was not to perform a full literature review, but to apply the case studies in an illustrative manner.

The search for the illustrative case studies was based on 'robust design' and 'case study' as search words in the Web of Science database as the main source of engineering journals. This search was limited to paper titles containing these search words and returned seventeen results. The search was further narrowed down to two criteria: studies performed on manufacturing industries and those concerning robust design as methodology. Finally, four papers were selected (Reddy et al., 1997; Menon et al., 2002; Yang, T. H. & Van Olmen, 2004; Lai et al., 2005) as illustrative cases for the purpose of the conceptual integration. First, the four papers were reviewed based on robust design strategies applied to each case and to all reported outcomes. Second, the outcomes were linked to RDM principles, product life cycle stages and sustainability dimensions: environment, economy and social. The links were then discussed by identifying the common aspects and the absence of the obvious links between RDM and SPD. This analysis resulted in the identification of three thematic areas for future research where RDM contributions to sustainability could be enhanced.

3.5 Trustworthiness

The trustworthiness of the method, data and analysis performed in terms of the validity and generalizability of the design of the case study will be discussed (Bryman & Bell, 2007).

During meetings and interviews, copious notes were taken, interviews were recorded and transcribed and the data analysis was performed based on the information retrieved. The result of the analysis was shared with the main contact person at the organization for agreement and confirmation. An analysis of these documents further confirmed the validity of the data through triangulation (Yin, 2009). The long-term involvement with the organization not only offered constant communication and access, but also a sense of trust between the researcher and employees involved in the studies. The accumulation of rich data was an outcome of this long-term involvement and access (Maxwell, 2005).

Since the business organization constitutes a single case study, the issue of generalizability of the research findings is of concern. One way to appease this concern may be found in the longitudinal nature of the case study (Leonard-Barton, 1990). The in-depth study at the business organization spanning a period in excess of two years produced rich and vast data, making it possible to address the research questions sufficiently. The quality of research was also dependent on the value created for those involved (Karlsson, 2008). RDM practices identified during the studies will serve as a platform for future robust design initiatives within the organization and will depart from a clearer understanding of the back-end data and their connection to noise factors.

4 Summary of Appended Papers

This chapter contains the summaries of three papers appended to this thesis. The summaries include the purpose, background, empirical material, findings and contributions of the papers. Some common themes identified are also presented. Readers are referred to the full papers appended for detailed information.

4.1 Paper I – Improvement in Product Development: Use of Back-End Data to Support Upstream Efforts of Robust Design Methodology

The purpose of Paper I was to suggest practices for the application of back-end data, such as customer claims, to support a front-end RDM approach.

The background chapter of Paper I focused on the characterization of QM based on certain principles implemented through a set of practices supported by a number of tools. Organizations that operate based on the customer-focused principle commonly involve their customers in the design process of product development, also known as the front-end. However, there is a need to focus not only on the front-end, but also on the back-end of product development in order to contribute to continuous improvement, another QM principle.

RDM, a methodology commonly applied at the design stage of products can be characterized by principles, implemented through practices and supported by tools. The continuous applicability principle of RDM aims at the application of systematic efforts to achieve insensitivity to noise factors at all stages of product development. Noise factors at the usage stage of products are not as easily identifiable as noise factors encountered during manufacturing. One way to capture and understand noise factors during product use is through the analysis of back-end data, such as customer claims.

The empirical setting of the case study is a medium-size organization in Sweden. Interviews were conducted with company personnel involved in the product development process and customer claims handling. Other data collection methods involved observation and hands-on experience during the inspection of defective products to further understand product defects and related noise factors. Further, an affinity exercise was carried out as a method of compiling unstructured verbal information based on the question: What are the major problems in using claims data for improvements?

The results of the study showed that there was a lack of systematic and structured customer claims analysis, an obstacle to using claims data to improve the design phase. The outcome of this study was the presentation of a systematic and structured flow of customer claims tied to a quality improvement tool, FMEA. A hypothetical example was presented based on the FMEA template used in product development within the organization. The systematic analysis of claims data led to the identification of root causes of the claims that were often related to noise factors affecting the products during usage. Corrective actions resulting from the FMEA could lead to product design changes or modifications, translating into improvements during the early stages of product development. The front-end improvement was based on the use of back-end data and was supportive of the continuous applicability principle of RDM.

4.2 Paper II – A Life Cycle Approach to Robust Design Methodology

The purpose of Paper II was to suggest an analysis of back-end data, such as customer claims, based on a product life cycle approach to identify noise factors in all stages of a life cycle.

Taguchi defines quality loss as the losses a product imparts to the society as a result of product failure during usage. Thus, the focus of RDM expanded from a single customer using the product to society at large. This view is relative to thoughts underlying SPD, where efforts to integrate sustainability considerations in the early stages of product design was emphasized to reduce environmental impacts throughout the product life cycle. Referring to the continuous applicability principle, there was a need for RDM practices throughout the product development process. However, RDM practices had widespread emphasis in the past on the front-end of product development, resulting in a lack of focus on how data derived from the back-end of product development may be used to support front-end robustness efforts.

There was often no shortage of back-end data, such as customer claims, but the challenges faced by organizations rather revolved around the lack of suitable ways in which to use the data for improvements. Claims data are a source of information relating to product failures and the conditions to which products are subjected during failures. This created an opportunity to use back-end data to understand the conditions during which products are used. In SPD efforts, a life cycle approach was commonly adopted. The systems approach was argued as necessary in order to recognize and address trade-offs of sustainability considerations at all stages of the product life cycle. Common stages of the product life cycle include raw material, manufacturing, distribution, usage and end-of-life, where a number of design strategies addressing sustainability considerations are found in the literature for each stage.

The empirical setting of this study was the same Swedish manufacturer as in Paper I. Two main interviewees involved in handling claims reports and maintaining the claims database were selected. The primary data collection method involved semi-structured interviews with questions on the functions and contents of the claims database. Further, the Quality Department Manager was interviewed to understand how claims data were utilized within the organization. All interviews were recorded and transcribed and notes taken. Several meetings were held with the main contact person at the organization to discuss and understand the failure modes related to the claims which were later used to identify possible noise factors related to product failures.

Access to the claims database was provided the researchers. The database was scanned for lists of failure codes, customers, claims received between 2006 and 2010, and claims reports generated for periodic top management review. A quantitative analysis on the claims data was performed by extracting the data from the claims database to statistical software called JMP. EDA was used as an analytical method in JMP, where claims data were graphically generated with the help of histograms. The goal of EDA was to discover patterns of data through their distribution in graphical format, where features of data that stood out, i.e. salient features, became the focus of interpretations.

Three salient features were identified from the distribution: the number of claims, failure modes, and frequently claimed products. The salient features were interpreted based on interview data and information gathered during meetings with the main contact person who was treated as the subject matter expert. Finally, failures from claims data were inductively related to possible noise factors, which were classified according to product life cycle stages. The results focused on a product called P4, which was identified as the most frequently claimed product based on EDA. The failure modes of P4 were classified according to its life cycle stages and possible noise factors identified, as shown in Table 4.

Table 4: Illustration of failure modes underlying claims of P4 related to life cycle stages

Failure mode	RM	Mfg	Dist	Use	EoL	Possible NFs
Abuse, overloading				■		Variation in loads Improper maintenance
Spring retainer loose				■		Improper maintenance
Normal wear					■	Wear and degradation
Faulty process		■				Variation in operator knowledge
Faulty tolerance		■				Variation in operator knowledge Poor quality in specification
Wrong delivery number/part			■			User training
Lack of maintenance				■	■	Poor vehicle owners procedure
Wrong installation		■				Variation in operator skill
Worn lifting arm				■	■	Variation in loads

The results showed that product failures could be related to various life cycle stages. Based on the life cycle stages, possible noise factors could be related to these failures. Examples of noise factors during the usage stage included variations in loads, such as exceeding the load limit of the product and improper maintenance due to user negligence. The variation between users, although using the same product was related to specific user styles and to differing ways in the maintenance and care of the product. Table 4 also showed that failures could be related to other life cycle stages than usage. For example, in the manufacturing stage, variations in operator knowledge, skills, and poor specifications were identified as noise factors. The use of back-end data, by an analysis of claims data based on the product life cycle approach was suggested as an RDM practice to identify noise factors. By identifying noise factors, this analysis formed the basis of action plans to address product claims by focusing on creating an insensitivity to noise factors.

4.3 Paper III – A Conceptual Integration of Robust Design Methodology and Sustainability

The purpose of this paper was two-fold. First, it was to explore how RDM efforts may contribute to sustainability and, more specifically, to SPD. Second, it was to propose a research agenda in order to develop the area of sustainable robust design.

Taguchi's definition of quality loss as the loss imparted by products to society from the time they were distributed was used to connect RDM to sustainability. The opportunities to contribute to SPD were possible through the integration of sustainability considerations into existing tools and methodologies. Although there were recent research attempts to identify the use of robust design for results supportive of sustainability benefits, they were rather fragmented and presented no unification in a broader sense. There is a need to reclaim Taguchi's idea of a categorization of noise factors based on a broad level of society, not a single user or customer in line with sustainability challenges.

In RDM, the importance of robust design efforts has been emphasized in designing products and processes. Similarly, sustainability efforts have moved upstream to the development and design stages of products, compared to earlier end-of-line efforts such as disposal systems. Design for Environment (DfE) strategies were defined based on the life cycle stages of products in order to consider design issues in terms of environmental safety and health during the development of new products and processes.

The conceptual method used in this paper was based on development classified as philosophical conceptualization integrating previous work on the same topic, summarizing the common elements and extending the work in some manner. The conceptual integration of RDM and SPD was based on the underlying ideas of each concept along with data from published case studies on RDM from the literature. The search for case studies was performed in the Web of Science by using the search words 'robust design' and case study'. The selection criteria were studies performed on the manufacturing industry concerning robust design. The search resulted in four papers used as illustrative cases for conceptual integration.

First, an overview of the cases classified according to the problem, robust design strategies and reported outcomes of the studies was presented. Second, the links of these cases to RDM principles, product life cycle stages and sustainability dimensions were presented, as shown in table below.

Table 5: Linkages between RDM principles, life cycle stages and sustainability dimensions

Source	RDM Principles	Outcomes	Robust design strategy	Impact on product's life cycle stage	Sustainability dimensions
Lai et al. (2005)	Awareness of variation (noise factor identification) Creating insensitivity to noise factors	Increased understanding of customer feelings and decreased sensitivity to customer variations in perceptions.	Use the feeling quality discrepancy as the response variable to be minimized. Explicitly consider various customer profiles as noise factors.	Product use	Economic Possibly social
Yang and Van Olmen (2004)	Awareness of variation Creating insensitivity to noise factors	Increased yield, less scrap.	Use quality yield as response variable to be maximized. Self-revealing noise due to replication.	Manufacturing	Economic Possibly environmental
Menon et al. (2002)	Awareness of variation (noise factor identification) Creating insensitivity to noise factors	Decreased early life failures and increased insensitivity to unit-to-unit noise.	Dual response approach was used to minimize cogging torque while achieving an acceptable amount of variance.	Product use	Economic Possibly environmental
Reddy et al. (1997)	Awareness of variation Creating insensitivity to noise factors	Decreased customer complaints. Less sensitive to customer variations (between different markets).	Taguchi method and multi-response optimization using goal programming. Self-revealing noise due to replication.	Product use	Economic Possibly environmental

The use of robust design resulted in better quality and reliability of products. Therefore, in general, the use of robust design contributed to economic sustainability. Alongside outcomes such as reduced scrap or decreased failure, there were links to environmental sustainability in terms of less material consumption and fewer disposals. However, the impact of RDM on societal sustainability was not obvious. Further, to enhance the contributions of RDM to sustainability, three areas of future research were suggested:

1. Reclaiming the view of quality loss as a loss to society and not a single customer.
2. Continuous applicability to the life cycle of a product.
3. Using sustainability indicators such as carbon emission as response variables in the multi-response optimization approach to robust design.

4.4 Common themes

A number of common themes have emerged from the studies done in the three appended papers. They are shown in Figure 2 below, and presented in this chapter.

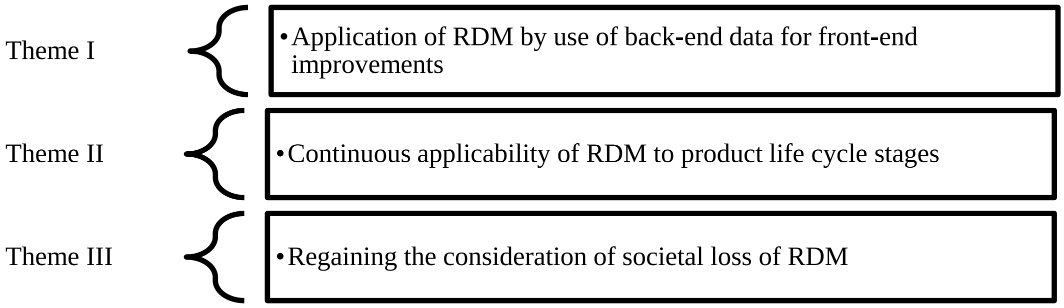

Figure 2: Common themes

Theme I – Application of RDM by use of back-end data for front-end improvements

The potentials of RDM are not limited to the front-end application and use of design tools such as DoE contributing to improvement efforts in product development. The use of back-end data such as customer claims creates an opportunity for the continuous application of RDM to all stages of product development, an area in need of additional research. Claims data is a source of information concerning products in the stage of usage, when critical product failure information is available. This information is often related to product quality or the lack thereof. In addition to specific product failures, claims data also offer information on conditions during failures, when failures occur and the failure of specific components within the products.

Designers and engineers become privy to knowledge that cannot be predicted during the design stage of product development. The knowledge is useful in creating an in-depth understanding of products in terms of field performance and robustness. With this knowledge, design considerations are informed and factual, as opposed to predictions based on assumptions. Such practice contributes to design improvements in consecutive product development.

Theme II – Continuous applicability of RDM to product life cycle stages

Assumptions made during the design stage in consideration of noise factors present a major challenge to designers and engineers. Noise factors are commonly classified into three categories: manufacturing variation, usage condition variation, and wear and degradation. Noise factors can be known, unknown, controllable or uncontrollable. With the exception to manufacturing variation, which is often easier to identify, possible noise factors are at best predicted during the design stage. Therefore, the critical activity of identifying noise factors is not a simple task.

The analysis of back-end data based on a product life cycle approach creates another opportunity for the continuous application of RDM. The application of back-end data is supportive of the complex task of noise factor identification. In addition to identification, noise factors are also found in various stages of the product life cycle. For example, a rusty component could be related to the usage stage, where an exposure to rain could be a possible noise factor in which case designers would not need to focus on correcting the design to counter the failure. Recurrence could rather be avoided by educating users on the proper maintenance and safeguarding of products. Another example would be a component not securely fixed onto a product due to faulty welding, which may be classified under the life cycle stage of manufacturing. The cause of the failure might be insufficient welding, and if so, the related noise factor could fall under the wear and degradation category. Designers privy to this knowledge would then be able to reconsider the steel quality of the raw material and engineers would be able to reconfigure the settings of the welding machine.

The continuous application of RDM is called for during all stages of product development. The life cycle approach allows the continuous application of RDM to all stages of the product life cycle by use of back-end data. The adoption of a product life cycle approach favors SPD efforts. In the example of the manufacturing stage, RDM leads to a reduction of manufacturing scrap. Less scrap equals lower waste of resources, leading to lower cost and increased profit. Therefore, the extended application of RDM by the use of back-end data and a product life cycle approach also contributes to SPD. Moreover, adopting a life cycle approach to identify noise factors opens up a wider range of opportunities for RDM efforts in product development activities. For example, possible RDM efforts during the distribution stage of the life cycle may extend the traditional approach of RDM focusing on products and manufacturing processes.

Theme III – Regaining the consideration of societal loss of RDM

The definition of quality loss as a loss to society partly caused by the harmful side effects of products as soon as they are shipped to customers was raised by Taguchi. Nowadays, the harmful effects of products are commonly viewed as being caused by product distribution, use, and disposal to the surrounding environment and society in which the products exist and function. Product distribution channels cross the ocean on cargo ships might pose threats to the natural environment by the excessive use of energy resources or unwanted ocean dumping. The use of air-conditioning units is harmful to the environment through the release of byproducts into the air. The disposal of mobile phones results in vast landfills of electronic waste unable to disintegrate into nature. Taguchi’s definition fits into the description of the above harmful side effects that create losses to society in the forms of ocean species extinction, air pollution, and land degradation.

Returning to the broader view of customers in RDM applications facilitates the integration of sustainability considerations into QM. Breakages of mobile phone components due to mishandling could be minimized by designing with considerations to the noise factor, which is likely to reduce scrap. The opportunities to apply RDM efforts has in the past been limited because of a narrow view on customers and a narrow focus on life cycle stages. By regaining Taguchi’s consideration of societal loss, including the distribution, use and end-of-life stages of the product life cycle, a wider range of loss prevention opportunities would open up with the help of RDM efforts.

5 Discussion

This chapter contains a discussion of the research findings in relation to the theoretical background. The discussion is based on the purpose of this thesis; to contribute to an extended application of RDM by the use of back-end data for front-end improvement and by exploring how RDM might contribute to SPD.

In most organizations, there is an extensive availability of back-end data, such as customer claims. A major challenge faced by engineers and managers is how to use such a wide range of data in ways that would support and contribute to improvements in product development (Zairi, 2000; Fundin, A. P. & Bergman, 2003; Fundin, A. & Elg, 2010). Papers I and II illustrate how claims data can be used to support front-end design improvements in product development. Paper I shows that the lack of a structured and systematic way to analyze claims data presents an obstacle to using the data for improvements within the organization. A claims data analysis tied to a quality improvement tool such as FMEA would be supportive of these improvements. FMEA is a problem solving quality tool (Ahmed, J. U., 1996; Bamford & Greatbanks, 2005) that could be applied to identify root causes of failures and possible noise factors for instances when claims data are used as input into the process using FMEA. An analysis of customer claims data tied to FMEA might lead to the identification of noise factors related to the causes of product failures. This recommended practice is also supportive of applying RDM efforts to the front-end of product development.

Paper II points out that customer claims data could be used to identify possible noise factors in various life cycle stages of products. This development is made possible through the analysis of claims data and the identification of product failures based on a product life cycle approach. Engineers and designers may neither foresee nor acknowledge the existence of certain noise factors during design stages which is acceptable in most operations because of unknown noise factors that are impossible to predict (Johansson, P. et al., 2006). This is a challenge in consideration during product usage, where products are exposed to varying conditions in which unknown noise factors may exist. Claims data contain information on product failures, their timing and under which conditions failures occur (Magniez et al., 2009). Analysis of claims data and root cause investigation of the failures could lead to increased understanding of product usage conditions, and possibly identification of some unknown noise factors (Wu, H. & Meeker, 2002). The analysis of claims data based on a life cycle approach leads to an identification of product failures in various stages of the life cycle, including raw material, manufacturing, distribution, use, or end-of-life. When failures are categorized in connection with the life cycle stages, possible noise factors causing the failures can also be identified throughout the life cycle stages. This process enhances the visibility of possible noise factors to not only designers and engineers working at the front-end of product development, but also to those involved in back-end activities such as manufacturing and distribution, resulting in the continuous applicability of RDM throughout product life cycle stages.

The use of back-end data not only contributes to new practices, but also supports the principles of RDM, e.g. continuous applicability (Hasenkamp, T. et al., 2009). The essence of this principle is that an awareness of variation and the creation of insensitivity to noise factors should be applicable to all stages of product development (Arvidsson & Gremyr, 2008). The extended application of RDM by the use of back-end data, as shown in Paper II, contributes to the development of RDM practices and to the application of RDM principles throughout all stages of the product life cycle. A life cycle approach would be required with regard to SPD for reasons of recognizing trade-offs and taking into account front-end and back-end activities in product development (Klöpffer, 2003; Azapagic et al., 2006). By identifying and managing noise factors leading to product improvements at all stages of the product life cycle, the suggested RDM practice in Paper II shows how RDM efforts might contribute to SPD.

RDM efforts further contribute to SPD in connection with certain underlying ideas. In Paper III, four published case studies on RDM based on a literature search (Reddy et al., 1997; Menon et al., 2002; Yang, T. H. & Van Olmen, 2004; Lai et al., 2005) were used as illustrations. The connection between the results of RDM applications and sustainability were established based on RDM principles, product life cycle stages and sustainability dimensions in terms of economic, environmental and social factors. All four case studies were related to RDM principles, such as an awareness of variation and creating insensitivity to noise factors (Arvidsson & Gremyr, 2008). The outcomes of the studies, a decreased sensitivity to customer variations, decreased early life failures, increased yield and less scrap and decreased customer complaints bears promise of economic benefits. Hence, economic benefits are identified. Less scrap and decreased early life failures show possible links to environmental sustainability in terms of less waste through product scraps.

6 Conclusion

This chapter presents a conclusion of the thesis, by addressing the three RQ’s: RQ1 - Can the use of back-end data be supportive of RDM? RQ2 - How can an analysis of back-end data be supportive of the continuous applicability principle of RDM? RQ3 - How may RDM efforts contribute to SPD?

The use of back-end data is suggested to be supportive of RDM. The use has been addressed by the suggestion of two practices. First, analysis of claims data tied to a quality improvement tool such as FMEA is suggested as a practice to support front-end improvements in product development. The analysis of claims data by the use of FMEA forms a basis for action plans to tackle the failures of products. Product failures during use are subjected to the usage conditions. The possible noise factors related to the failures in use conditions can then be identified for improvements in the product design stages. Second, an analysis of claims data based on a product life cycle approach is suggested as a way to identify possible noise factors in all stages of the life cycle. This practice is supportive of the continuous applicability principle of RDM throughout all stages of the product life cycle. Both practices contribute to an extended application of RDM.

The adoption of a product life cycle approach to identify noise factors shows how RDM might contribute to SPD. By identifying and tackling noise factors during certain stages of the life cycle, for example the manufacturing and use stages, a systems approach to minimizing waste or reducing scrap is presented. Further, the conceptual integration of RDM and SPD reveals possible links between the two. Results from previous case studies on RDM based on a literature search were used to illustrate possible links to sustainability.

An extended application of RDM would require three additions to current views; an increased focus on back-end data, an increased focus on practices and the adoption of a life cycle approach. The extended application of RDM to back-end activities, such as customer claims analysis, facilitates a front-end design improvement to product development. Practices such as a systematic and structured analysis of back-end data and an analysis based on a life cycle approach contribute to an extended application of RDM. The adoption of a life cycle approach to identify noise factors also contributes to SPD. A life cycle approach would present new ways in which to identify and tackle noise factors during product development. Hence, a life cycle approach is seen as one way of extending the traditional methods used to identify possible noise factors.

7 Future Directions

Currently, there is substantial literature in the field of QM that discusses the possible integration with sustainability and environmental requirements. In fact, the same discussion is also found in the area of Operations Management. A literature review regarding the integration of sustainability considerations into QM may be an area of interest. By pointing to new RDM practices to be integrated into product development work, this study may result in new ways of addressing the use of RDM for sustainability benefits.

A future area of interest involves organizing RDM as a specialty competence in product development. The aim is to understand how RDM could be organized as a specialty competence that can be effectively integrated into product development work and could possibly contribute to the identification of new RDM practices in product development and continuous applicability. Further, organizing sustainability considerations in product development is seen as an area of specialty competence in most organizations. In a study of such product development competencies, RDM could be coordinated with sustainability competence to contribute to exploitation of identified linkages between RDM and SPD.

The application of RDM has been commonly perceived by practitioners as technical and experimental. This perception is largely based on the notion that RDM concerns the application of tools, specifically tools such as DoE and the Taguchi method. These tools are based on statistical experiments requiring some knowledge of statistical tools. By shifting the focus from tools to RDM principles and practices, a change in the mindset of practitioners would be required in applying RDM. This change of focus may increase the acceptance of RDM in terms of variation and noise factors, as opposed to statistics and experiments. However, future research is then needed to develop some indicators or measures of robustness in line with the qualitative approaches.

This research was based on a longitudinal study in a single case organization. A future research in this area could be extended to include more organizations for multiple case studies. In doing so, the suggested RDM practices and the possible links between RDM and SPD could be adopted and refined further in other contexts. The multiple cases may contribute to more possibilities of RDM practices, and other potential links to SPD.

Finally, it may be of interest to further study the relationship between high quality and robustness, and customers' wants in terms of new products. Many organizations exist for the reasons of sales of products and profits. Products are constantly upgraded in order to increase sales and profits. In the example of mobile phones, the developers and designers are known and expected to constantly upgrade and release newer versions of the mobile phones. The quality of products in terms of their usability and fashion comes into play, where older versions of the products are no longer desired, although they are robust and with long lifespan which is beneficial from a sustainability point of view. A future research could address and problematize this relationship between the robustness and customer wants in terms of new products and high profits.

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