
A life cycle approach to robust design methodology

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Abstract: This paper proposes a new practice of robust design methodology (RDM); to adopt a life cycle approach to noise factor identification. Such practice expands the boundary of traditional use of robust design where noise factors are generally known, observable and experimentally controllable. By exploiting information from claim data of a medium-sized Swedish manufacturing company, several other noise factors were identified and classified into product life cycle stages; factors that are often uncontrollable, unobservable, or unknown. Exploratory data analysis, interviews, and internal documents are used in this study. The results show that by analysing the claims data, the product's failure modes can be identified and classified into various product life cycle stages. This enables identification of noise factors in each product life cycle stage. The use of a life cycle approach has two major implications. One is to expand the focus of RDM to encompass all product life cycle stages instead of being limited to a product development process. The other implication is that the practice proposed facilitates consideration of more stakeholders, in addition to one single customer by looking at consequences for society at large once the product is in use. Hence, the proposed RDM practice can be supportive of sustainable product development.

Keywords: robust design methodology; RDM; life cycle approach; noise factors; sustainable product development; back-end data.

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1 Introduction

Genichi Taguchi, who is known as a pioneer of robust design methodology (RDM), defines quality as the losses a product imparts to the society resulting mainly from product failure during usage (Taguchi and Clausing, 1990). In other words, the focus of RDM is not only limited to losses to one single user, but also to the society at large. RDM has been known as a useful tool supportive of upstream quality efforts (Arvidsson and Gremyr, 2008; Hasenkamp et al., 2009), i.e., efforts during product development. This is well in line with the thoughts underlying sustainable product development (SPD) where the emphasis of environmental impacts have shifted from end-of-life strategies such as recycle and waste management to upstream efforts of integrating sustainability considerations in product design (Johansson, 2002).

Practices of RDM in early phases of product development have come into focus lately (Hasenkamp et al., 2009). However, there are noise factors, e.g., related to use phase that are not easily identified through front-end efforts. Not much emphasis has been given to how data derived from the back-end of the product development process can be used to support front-end robustness efforts, e.g., by supporting identification of noise factors occurring during product use. Back-end data is defined here as production data as well as claims data from customers during the product use stage. In organisations, there is often no shortage in availability of such data. Rather, scarce attention is given to the role of back-end data in providing feedback to product and process quality issues (Saccani et al., 2006), and there is a lack of use of the data to drive improvements (Fundin and Bergman,

2003). Customer claims data is a source of information from the product use stage, creating opportunity to understand the conditions in which products are used. These conditions vary in its effect on products, from optimal for product usage to conditions causing failures of products. The conditions related to or causing failures are, at times, referred to as noise factors (Phadke, 1989).

In efforts to achieve SPD, a life cycle approach is commonly adopted (Klöpffer, 2003). In this adoption, a product is categorised based on various life cycle stages, namely raw material, manufacturing, distribution, use and end-of-life. Analysis of customer claims data allows retrieval of information on failures modes. These failure modes and their causes can be related to one or more stages of a product life cycle. Hence, the related noise factors could also be linked to one or more stages of life cycle.

The purpose of this paper is to propose a new practice of RDM by adopting a life cycle approach to noise factor identification. Such practice expands the boundary of traditional use of RDM where noise factors are generally known, observable and experimentally controllable (Johansson et al., 2006). By exploiting information from back-end data (i.e., claim data) of a medium-sized Swedish manufacturing company, we identified several other noise factors which are often uncontrollable, unobservable, or unknown and classified them into product life cycle stages. Exploratory data analysis, interviews, and internal document analysis were used in this study. The practice suggested addresses two research niches; lack of practices of RDM to use back-end data as a means to support its continuous application throughout product life cycle, and limited elaborations on links between RDM principles and sustainable product development (Gremyr et al., 2014).

This paper contributes to RDM by taking a product life cycle approach when identifying noise factors; pointing to noise factors influencing various stages which can provide opportunities to continuously work on achieving robustness. More generally, identification of noise factors throughout product life cycle stages may contribute to increased knowledge on what affects product performance over its entire life cycle.

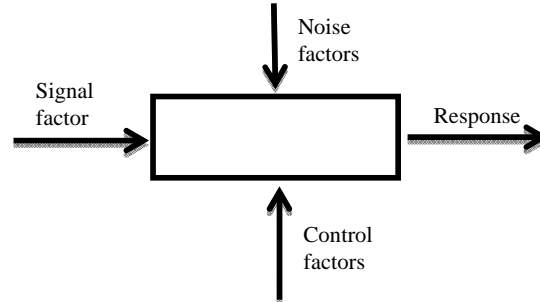
This paper is structured as follows. Section 2 provides the theoretical background. Section 3 describes the research methodology. The results of the claims data analysis are presented in Section 4, followed by discussions and conclusion in Section 5.

2 Theoretical background

The theoretical background addresses three main themes: RDM, back-end opportunities, and product life-cycle approach.

2.1 Robust design methodology

According to Taguchi, the definition of robustness is “the state where ... the product ... performance is minimally sensitive to factors causing variability ... and aging” [Taguchi et al., (2000), p.4]. Based on this definition, robustness is achieved when variations are taken into consideration during product design stage. Sources of variation that can be controlled are referred to as control factors; whereas those that cannot be controlled or are expensive to control are referred to as noise factors (NFs). A P-diagram is often used to conceptually analyse NFs and their influence on a product or process, as shown in Figure 1 (Phadke, 1989).

Figure 1 P-diagram

NFs can be classified based on their manifestation environment and degree of knowledge (Johansson et al., 2006). According to their manifestation environment, NFs can be classified into those in-production (e.g., manufacturing imperfections that cause unit-to-unit variation) and those in-use (e.g., external conditions such as user-to-user variation, and internal conditions such as product wear and degradation during usage). According to the degree of knowledge, NFs can be divided into sub-categories of known and unknown, where known factors are divided into observable and unobservable. The observable NFs are then divided further into experimentally controllable and uncontrollable.

Experimental tools, such as design of experiment, are applicable for assessing the NFs that are known, observable, and experimentally controllable. This leaves out various other NFs which are unknown, unobservable, and uncontrollable. Furthermore, despite the fact that noise factor identification is a critical activity in RDM (Taguchi and Clausing, 1990), a lot of the efforts to date have been focused on improving existing statistical techniques in creating insensitivity to NFs (Tsui, 1992) with rather little emphasis on practices supporting the actual identification of NFs.

In general, RDM is described as a front-end approach to reduce performance variation in products and processes (Shoemaker et al., 1991; Andersson, 1996; Goh, 2002; Park et al., 2006; Amuthakkannan, 2012; Shahin, 2012). In a conceptual discussion on RDM, a need has been raised to explore applications of RDM based on its underlying principles (Arvidsson and Gremyr, 2008) and to increase focus on practices of RDM as opposed to a main focus on tools (Hasenkamp et al., 2009). In fact, a clear gap has been identified in the lack of practices related to RDM application. More specifically, there is a lack of practices supporting continuous applicability of RDM throughout product development stages (Hasenkamp et al., 2009). This creates a need for RDM practices to focus on, not only the front-end of product development, that is the design stage, but also the back-end (Siva, 2012).

2.2 Back-end opportunities

Product development activities are conducted in a continuum which could be divided into front-end and back-end of development (Cooper and Kleinschmidt, 1986). Both ends are critical in establishing successful development efforts, e.g., after-sale stages is a source of knowledge that can be tapped into (Poolton and Barclay, 1998). One source of knowledge from the back-end is customer claims data related to product failures in the

field. A number of opportunities for improvements could be found in analyses of field data such as customer claims (Fundin and Bergman, 2003; Fundin and Elg, 2006, 2010). A main challenge faced by managers concerning claims data is not in the availability of data, but rather in answering the question of what could be done with the data, and how (Fundin and Bergman, 2003). This is related to the lack of a systematic approach for customer claims handling in many organisations (Zairi, 2000).

Information regarding failures of products, conditions of use during failures, and failures of specific components are valuable information in the improvement of product reliability and quality (Meeker and Escobar, 2004). In the design stage, designers are able to anticipate certain failures and make relevant design considerations to counter the failures. This is not the case for all failures. Unexpected failures occur in the field, e.g., due to variations in conditions of use, mishandling, or wrong use of products. The information concerning such incidents may be captured in the claims data, which is beneficial in understanding the reliability of products. A need of a reliability-oriented feedback system is required in order to improve design work (Magniez et al., 2009). Feedback from claims data should also be seen as a critical information channel, where flow of information from customers to various functions involved in product development can take place (Molenaar et al., 2002).

2.3 Product life cycle approach

SPD has developed from discussions of consumption imbalance of natural resources in the world (Van Weenen, 1995) to integration of sustainability aspects in existing product development tools based on product life cycle approach (Luttrupp and Lagerstedt, 2006). Integration of sustainability requirements in existing tools and methodologies is one way to contribute to SPD efforts (Masui et al., 2003). This integration is argued a necessary step in all stages of a product life cycle in order to support SPD (Kaebernick et al., 2003). An example of a life-cycle-based methodology is life cycle assessment (LCA); widely recognised as a way to assess environmental impacts of products and processes (Kaebernick et al., 2003; Vinodh and Rathod, 2010).

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). A product life cycle refers to the stages that a product “followed from its ‘cradle’ where raw materials are extracted from natural resources through production and use to its ‘grave’” [Baumann and Tillman, (2004), p.19]. The product life cycle approach in reducing environmental impacts is often discussed as a beneficial approach towards SPD (Kaebernick et al., 2003; Bhamra, 2004).

The systems view in a life cycle approach is argued necessary to maintain a balance by focusing on all stages of product life cycle in addressing sustainability considerations (Klöppfer, 2003). Klöppfer (2003, p.134) stated that

“any environmental, economic, or social assessment method for products has to take into account the full life cycle from raw material extraction, production to use and recycling or waste disposal. In other words, a systems approach has to be taken. Only in this way, trade-offs can be recognised and avoided. Life cycle thinking is the prerequisite of any sound sustainability assessment.”

Common stages of a product life cycle comprise of raw material, manufacturing, distribution, use, and end-of-life (Choi et al., 2008). A number of strategies have been identified by Choi et al. (2008) in addressing sustainability considerations in each of these stages, as shown in Table 1.

Table 1 Life cycle stages and strategies

<i>Life cycle stages</i>	<i>Strategies</i>
Raw material (RM)	Reduction of material use Use of recycle and recyclable material Avoid toxic or hazardous substances
Manufacturing (Mfg)	Avoid waste of material Clean production Minimised variety of material
Distribution (Distr)	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 (EoL)	Re-use and recycle Remanufacturing Safe disposal

Source: Choi et al. (2008)

3 Methodology

This section is divided into two main sections. The first comprises of methods applied in the process of collecting interview data; followed by a second section on collection and analysis of the claims data.

3.1 Interview data

One data collection method was interviews, aiming to understand the functions of the claims database within the organisation. The interviews were of a semi-structured type, i.e., the overall questions were specified to cover the intended themes whereas detailed questions within the themes can vary between interviews. The pre-defined overall questions can be found in Appendix. The questions were formulated to gain knowledge of the claims handling process, in terms of input data, data entry process, frequency of data entry, and the way the claims data was processed and utilised in terms of claims authorisation, report generation, claims data update and maintenance of database.

The two main interviewees were directly involved in the claims handling process. They were responsible for claims data entry and handling of claims for two different customer segments. The interviews took between three to four hours each. The

interviewees were continuously consulted by the authors, and asked follow-up questions for further clarifications as and when necessary.

The quality manager at the organisation was added as another interviewee to further understand the current challenges in using the claims data for improvement purposes within the organisation. The interview covered the same areas as described above, see Appendix. This interview lasted two hours. Several meetings were held with the main contact person at the organisation, who was an engineer responsible for product and process improvement initiatives within the organisation. These meetings usually lasted between two to three hours each session, in a total six full day visits. Interviews and meetings were conducted in English. All interviews were recorded and transcribed.

The interviews provided insights into the claims handling process, whereas the data analysis elaborated on in the following subsection was used to explore potentials of the claim data in supporting RDM. This analysis will further be the basis for developing the proposed RDM practice.

3.2 Claims data

The claims data was extracted from the Microsoft Access database and imported to statistical software (JMP), for quantitative analysis. The dataset analysed in this study contained claims data of five years, from 2006 until end of 2010. It includes claims within and without the guarantee period; allowing for analysis of data from a broad range of life-cycle stages. The database was explored by studying the lists of failure codes, customers, and various claims reports stored in the database, including reports on claims generated for periodic top management review.

The analysis of a large dataset was done in an exploratory manner, where there is a need to understand what is going on by looking at the data. In such situation, EDA has been advocated to be a fitting analysis method (Tukey, 1962). The goal of EDA is to discover patterns in data through 'listening' to the data in as many ways as possible until a plausible 'story' of the data is apparent (Behrens, 1997). In the process of EDA, a number of steps can be discerned, namely display of data, identification of salient features, and interpretation of those salient features (De Mast and Trip, 2007). Salient features refers to features that stand out from what was expected a priori (De Mast and Kemper, 2009). In this step of the process, a neutral reference distribution is identified. A reference distribution reflects an existing knowledge about the phenomena under study but is neutral with respect to other features. The third step of the process is essentially a non-statistical one, which is to theorise and speculate on the causes of patterns identified from earlier step. Interpretations of patterns or causes identified require expert knowledge of the subject, as stated in the fourth principle of EDA (De Mast and Kemper, 2009).

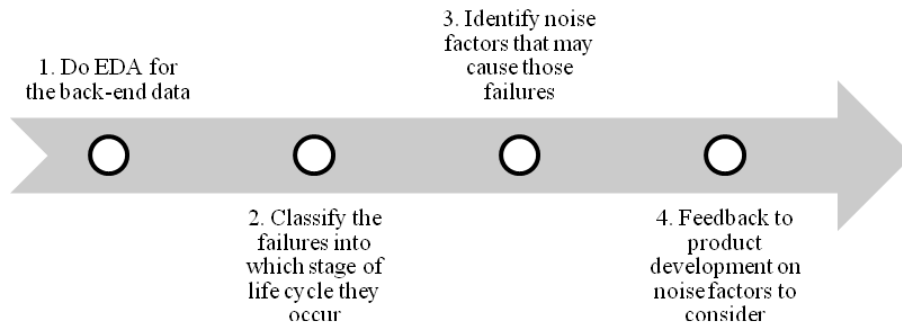
The EDA steps were applied in the analysis in JMP, where data was displayed through distribution, in the graphical form of histograms in order to capture patterns, and identify salient features. In the use of EDA, ideas are generated through confrontation between empirical data and subject matter knowledge (De Mast and Kemper, 2009). The histograms derived from the data analysis were analysed based on data collected through interviews and information gathered from meetings.

As a final step in the data analysis, failures are inductively related to possible noise factors based on remarks in the claims database on the situation in which the failure occurred. The failures, and related noise factors, are classified according to the life cycle

stages. As part of the validation, the results from this step were discussed with the main contact person at the organisation, who was a subject matter expert.

The proposed practice of analysing claims data by the EDA method in order to identify noise factors specific to certain life cycle stages is summarised in Figure 2.

Figure 2 The practice summarised in steps: 1) EDA for the back-end data, 2) failures classified based on life cycle stages, 3) noise factor identification, and 4) feedback to product development



4 Results

Display of claims data in histograms enabled identification of salient features. The first attempt of visualising the data led to several findings including the identification of most problematic areas of claims categorised by customer, failures modes, and parts. For the sake of simplicity further analysis will focus on the number of claims by parts. The analysis will illustrate how the claim data analysis may lead to the identification of noise factors throughout product life cycle.

Figure 3 shows a truncated histogram of number of claims of a total of 109 parts from 2006 to 2010. Note that the parts' names are not shown in the histogram due to confidentiality reason. For ease of reference, a set of codes such as 'P1', 'P2', ..., 'P5' is used to refer to the highest number of claims, second highest, and so forth (see Table 2).

Figure 3 Truncated histogram of number of claims by parts from year 2006 to 2010 (see online version for colours)

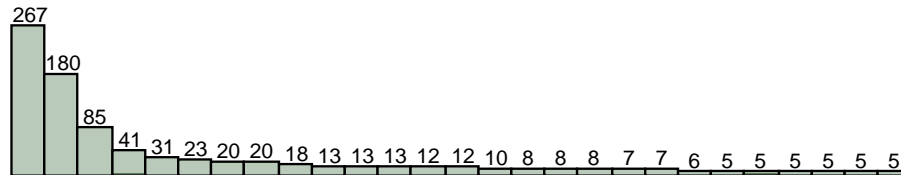


Table 2 Percentage of claims by parts adjusted by sales data

<i>Part</i>	<i>Number of claims</i>	<i>Number of sales</i>	<i>% of claims</i>
P1	267	25,941	1.03
P2	180	19,908	0.90
P3	85	5,880	1.45
P4	41	1,011	4.06
P5	31	13,971	0.22

It is not difficult to see that the number of claims by parts may depend on how many units were sold for a particular part. In other words, one may not conclude directly that the first part (P1), which has a total of 267 claims, is the most problematic one. After some discussions with the subject matter expert, it was found out that the number of claims by parts should be adjusted by the sales figures. In this case, the sales figures serve as the neutral reference distribution in the sense that the number of units for each part is more or less the same. However, as can be seen in Table 3, the number of units for each part differs a lot from each other. This led to the finding that 'P4' is the most problematic part.

Having identified 'P4' as the most problematic part, a further analysis of the claims pointed to a number of influential noise factors. As described above, noise factors, according to their manifestation environment, are generally classified into those 'in-production' and those 'in-use'. Knowledge about as many noise factors as possible is critical to support continuous applicability of RDM throughout product development. For claims data analysis, the most obvious category of noise factors underlying the claims is 'in use'; as it concern claims from the field. However, the root cause of the problem underlying the claims might well have arisen in other life cycle stages than use stage. Further analysis of 'P4' was structured based on the life cycle stages (raw material, manufacturing, distribution, use and end-of-life). Hence, the analysis supported identification of noise factors throughout the life cycle stages and consequently can be supportive of continuous applicability of RDM. Table 3 displays parts of this analysis as an illustration; containing failure modes causing claims of 'P4'.

Table 3 reveals that failures modes can be related to various life cycle stages, and hence various noise factors can therefore be related to these failures modes. Examples related to the use phase are various conditions of use such as long haulage, distribution of merchandise, logging, off-road and construction sites usage. Moreover there are variations in between users although using the product for the same purpose; this is often related to driver style, maintenance and care of the product. All of these variations being related to the use phase, Table 3 also points to the need to focus at the other life cycle stages in analysing some failures. An example is the manufacturing stage where noise factors related to manufacturing conditions come into focus, exemplified by variation in operator skills. This type of analysis leading to identification of a set of noise factors can form a basis for action plans to address the high number of claims of 'P4' by attempting to create insensitivity to the noise factors.

Table 3 Illustration of failure modes causing claims of P4 classified into life cycle stages

<i>Failure mode</i>	<i>RM</i>	<i>Mfg</i>	<i>Distr</i>	<i>Use</i>	<i>EoL</i>	<i>Possible NFs</i>
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

5 Discussions and conclusions

Viewing RDM as a way to minimise quality loss imparted to society (Taguchi and Clausing, 1990) can contribute to sustainability, but raises a need to study not only what happens when the product is produced and used, but also what happens in other life cycle stages, for example, in distribution or end-of-life stage. This is in line with notions on the need to extend applications of RDM to exploit opportunities to create robustness throughout a product development process (Clausing, 1994). This paper adds to this by applying a product life-cycle approach (Klöpffer, 2003), and not limiting the work on robustness to addressing opportunities in a product development process. Hence, continuous applicability, one of the principles of RDM (Arvidsson and Gremyr, 2008) is re-defined to account for all product life cycle stages instead of a product development process.

Specifically, the practices proposed in this paper are related to the use of back-end data. Not only does it support a view on RDM as concerning various stages of a product's life, it has also been identified as an untapped source for improvements (Poolton and Barclay, 1998; Fundin and Elg, 2006). This study contributes by linking back-end data to RDM, as a critical source to information of noise factors across product life cycle stages. Moreover, the claim analysis can be supportive of the continuous applicability principle of RDM in the product development process of the organisation. The claims analysis constitutes one way of getting customer feedback concretely linked to improvement activities, contributing to improved quality in subsequent product development projects.

To further investigate the relationships between various departments of the organisation with respect to using the results from claims data analysis is an area of future research. More test cases in other settings or companies will certainly provide better evidence for justifying the advantage of the proposed practice in addressing quality problems and possible noise factors.

To sum up, this paper has proposed a new practice of RDM by adopting a life cycle approach to noise factor identification. The use of life cycle approach has two major implications. First, it expands the focus of RDM to encompass all product life cycle

stages instead of being limited to a product development process. This helps identify noise factors throughout product life cycle stages, of which some were uncontrollable, unobservable, or unknown, in addition to the traditional noise factors which are generally known, observable and experimentally controllable (Johansson et al., 2006). Second, the suggested approach facilitates consideration of more stakeholders in addition to one single customer, as it focuses on the whole life-cycle and therefore can also capture long-term effects, e.g., on the environment. Hence, such attempt, we believe, can support RDM practice towards sustainable product development.

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Appendix

List of main questions used during semi-structured interview

Main questions to two interviewees involved in claim handling process

- 1 How often is claims data entered into the system?
- 2 What actions are taken during claims handling?
- 3 What types of reports are generated from the claims database?

Main questions to quality manager

- 1 How does your department handle claims?
- 2 How do you categorise the failures identified in claims reports?
- 3 What are the actions taken to address a quality defect identified in the claims?