# Robust Design Methodology for Sustainability

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## Abstract

A key principle in Quality Management (QM) is customer focus and much research has aimed at techniques supportive of this principle. One example of a research area within QM focused on developing such techniques is Robust Design Methodology (RDM). Taguchi, an early proponent of robust design defined quality in a way that differs from others, i.e. as loss to the society caused by the product, thus not being restricted to an individual customer. Today, this definition seems to be well in line with the sustainability challenges in all disciplines. Thus, it is time to enhance RDM to again focus on preventing losses to the society and thereby contribute to sustainability. The purpose of this paper is to explore how RDM may support Sustainable Product Development (SPD) and thus propose a research agenda for enhancing quality practices towards sustainability. The house of quality is used as a research instrument; identifying linkages between RDM and SPD. Some examples of the findings include the strong relationship between clean manufacturing and all RDM strategies, and the need to broaden the scope of traditional RDM with respect to material use. Finally, a future research agenda towards RDM for sustainability is proposed.

Keywords: Quality Management, Robust Design Methodology, Sustainable Product Development

## 1. Introduction

A key principle in Quality Management (QM) is customer focus. Hence, many definitions heavily emphasize the customer as an arbiter of quality. An early description of quality [1] (p. 53) is “One of these [aspects of quality] has to do with the consideration of the quality of a thing as an objective reality independent of man. The other has to do with what we think, feel, or sense as a result of the objective reality. In other words, there is a subjective side of quality.” The subjective side of quality has generally in the quality management area been interpreted as the needs and wants of individual customers. Dean and Bowen [2] (p. 394) defines total quality as “a philosophy or an approach to management that can be characterized by its principles, practices, and techniques. Its three principles are customer focus, continuous improvement, and teamwork”.

Much research has then been focused on the techniques of quality management, putting it bluntly how companies should improve quality. One example of a research area focused on developing techniques is Robust Design Methodology (RDM) [3]. Taguchi, an early proponent of the importance of robustness defined quality in a way that profoundly differs from other early proponents of quality in terms of its principles. Taguchi [4] (p. 1) defines quality as “the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions”. In his definition, the customer as the final arbiter of quality has not been replaced, but significantly expanded as quality is connected to the society, not only to an individual customer. However, he does not elaborate on the role of society at large but states that “what functions society should allow products to have is a cultural and legal problem, not an engineering problem” [4] (p. 3).

However, losses to society in terms of, for example, environmental damage has today reached proportions that makes sustainability a challenge of utmost importance for all disciplines including those of engineering. In the development and production of goods, there are possibilities to make changes that support sustainable development, which is often defined as the “ability to make development sustainable, to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" [5] (p. 24). Sustainable development is essentially grounded in achieving the triple bottom lines of economic, environmental and social development.

Furthermore, many authors, for example [6] and [7], argue that the way forward is to integrate sustainability in the existing tools rather than having a separate toolbox. This implies that the key to plenty opportunities to contribute to sustainable development lies in the elaboration and adaptation of sustainability dimensions in the existing engineering practices and techniques. In the RDM literature, studies on how RDM may contribute to sustainability are still very rare despite their importance today. The purpose of this paper is two-fold. First, it is to explore how the practices of RDM may contribute to sustainability and, more specifically, sustainable product development (SPD). Second, it is to propose a research agenda in order to fully explore and develop the area of sustainable robust design. The outline of the paper is as follows. Section 2 describes the method used for the study. Afterwards, the key concepts of SPD and RDM are elaborated in Section 3 and Section 4, respectively. An analysis of their interrelationships is carried out in Section 5 using the house of quality. The paper is concluded by a discussion and a proposal of an agenda for future research in Section 6.

## 2. Method

This paper is based on what Meredith [8] (p. 8) refers to as a conceptual method; in this case the conceptual model developed could be classified as philosophical conceptualization integrating "a number of different works on the same topic, summarizes the common elements, contrasts the differences, and extends the work in some fashion". In this paper, two concepts related to development of products – RDM (Robust Design Methodology) and SDP (Sustainable Product Development) – are subject to this conceptualization. The instrument applied to structure the conceptualization process is the house of quality (HoQ) from the field of Quality Function Deployment (QFD). The HoQ is described as "a kind of conceptual map that provides the means for inter-functional planning and communication"[9].

The basic construction of the HoQ can be found in the vast available QFD literature, for example [10] or [11]. Generally, the HoQ is used to map customer needs into a set of quality or technical characteristics for overall customer satisfaction. In this paper, it is used to map the main components of sustainable product development, which can be perceived as customer needs, into robust design methodology strategies, which exemplify a possible way to address the needs. The rationale is that we would like to address the way robust design methodology may contribute to sustainable product development. The HoQ will explicitly show if there is any relationship between RDM strategies and SPD components and the strength of the relationship. The strength of the association between the RDM strategies and the SPD components is judged based on available information in the literature with the support of daily life examples. In the end, it will also provide useful information on the importance ranking of RDM strategies in meeting the SPD components.

## 3. Sustainable Product Development

Since the early 1990's, aligned with the boom in sustainable development initiatives, environmental concerns have been interspersed in the development and manufacturing of products. The term 'green product' is widely used with regard to research and practices of manufacturing "environmentally friendly" products [12]. On the subject of environmentally conscious design or eco-design, much focus has been on integration of environmental impacts on existing engineering tools such as the Kano model, Quality Function Deployment (QFD) and Theory of Inventive Problem Solving (TRIZ). The enhancement of existing tools is seen as an approach to addressing the gap between the demand for tools and emerging theories such as Eco-design [13, 14]. Integration of sustainability aspects has been argued as a necessary step in all stages of a product's life in order to reach new levels of sustainability or overall sustainable manufacturing [15]. One possible way of achieving this is through integration of sustainability requirements in existing tools and methodologies towards contributing to sustainable product development [16].

Sustainability efforts at production stage alone are not sufficient in addressing product life cycle requirements and capabilities. A step backward in this flow is necessary in order to integrate sustainability aspects into life cycle requirements. This necessitates a re-visit and re-structure of the product development process to accommodate the sustainability aspects. In early literature, sustainable production was defined as an integrated approach where environmental requirements are considered in every stage of product development [17]. Manufacturers and designers have stepped into the responsibility of producing products and services, not only based on profit and margin factors but also the environmental factors. Moving from earlier efforts of 'end-of-line' sustainability initiatives and measures, such as emission control and product disposal system, sustainability aspects have moved upstream to development or design stages of products [18].

One particular method used for integration of environmental considerations at the design stage is called Design for Environment (DfE). Design for Environment has been defined as “systematic consideration during new product and process development of design issues associated with environmental safety and health over the full product life cycle” [19] (p. 126). Based on product life cycle stages, from raw material to disposal, five DfE strategies have been defined [20] (see Table 1 below).

**Table 1. Design for environment strategies (adapted from [20])**

| Life cycle stage | DfE Strategies |
|---|---|
| Raw material | Material use optimization |
| Manufacturing | Clean manufacturing |
| Distribution | Efficient distribution |
| Product use | Clean use/operation |
| End of life | End of life optimization |

In this paper, these five DfE strategies (Table 1) are adopted to be the main components representative of SPD initiatives in all stages of product life cycle. During the stage of raw material, SPD includes material use optimization as a design factor, where selection and bill of material are considered based on its environmental effectiveness and property appropriateness to recycling or remanufacturing, for example. During manufacturing, each process is designed to be robust to variations, such as protection against operator variability, minimization of material wastage and machine utilization optimization, to name a few. Distribution of finished goods in terms of weight of product in packages is taken into consideration during design stage in an attempt to maximize efficiency of goods transportation through utilization of less space in containers or trucks. In the product use stage, the user variation and usage conditions must be taken into consideration to ensure that wastage is controlled or minimized during product use. Product end of life strategies must be in place in order to optimize disposal methods. Recycling, reusing or remanufacturing options, for example, must be considered during design stage in order to address disposal of end products.

## 4. Robust Design Methodology

In order to relate RDM to SPD, three main concepts or models underlying this framework are reviewed. It can be said that each of them answers to a fundamental question related to RDM. Thus, why is it important to deal with variation? The answer can be understood through the concept of a quadratic loss function. What causes unwanted variation? The concept of noise factors, often within a P-diagram, is fundamental to answering this question. Finally, the concept of off-line and on-line quality control contributes to an answer to “When should actions be taken to reduce unwanted variation?”

### 4.1 The concept of Quality Loss

A number of authors over time have argued that unwanted variation among units of the same product will lead to dissatisfied customers [1, 21]. To take into account that noise factors cause a product characteristic to deviate from its specified target, a tolerance interval is assigned to a target. In the terminology of Taguchi, these deviations cause quality losses. Quality loss is defined in [22] (p. 4) as “the amount of functional variation of products plus all possible negative effects, such as environmental damages and operational costs.”

As discussed in Kackar [23], a traditional view of quality loss is that it is zero while inside the tolerance interval. An alternative view of target values and tolerance intervals is the quadratic loss function proposed by Taguchi [4, 24]. Viewing quality losses by means of the quadratic loss function results in more than two distinct levels of quality loss; the level varies depending on the distance from the target value. Illustrated by means of customer satisfaction, quality loss means that the customer is most satisfied if the performance characteristic is on target and gradually more dissatisfied when the value approaches the tolerance limits.

It is, however, important to consider the meaning of the customer in the sense of quality loss. It is often regarded as if the customer is the one buying the product, whereas other customer could also assume roles as users, co-producers, resources or even an outcome (e.g. a healthy patient is the outcome of a healthcare service) [25]. Moreover, Taguchi

[4] (p. 1) does not relate quality loss only to the customer but to the society at large, which is affected, for example, by the way the products are used or how they are discarded.

### 4.2 P-diagram

The desired levels of product characteristics are usually referred to as target values [23]. However, sources of unwanted variation might cause characteristics to deviate from their target values. These sources are often referred to as noise factors (NFs) in robust design studies. One way to conceptually analyse the NFs and their influence on a product or process is by the use of the P-diagram (see Figure 1) relating the input to a system (signal factor) to a desired response, simultaneously considering control factors and NFs [21]. In other words, signal factors as inputs are related to the response variables, as the output, considering both NFs and control factors. Later versions of the P-diagram also add as an output various error states, i.e. undesired outputs [26].

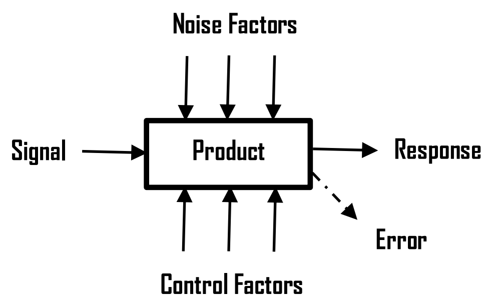


**Figure 1. P-diagram**

NFs are often categorised as a means of facilitating their identification as well as describing the main areas in which they arise. Probably the most famous, and used, categorisation is that by Taguchi and Wu [24] into outer disturbances, manufacturing disturbances, and inner disturbances. This way of labelling the categories is rather open in that it allows for identification of outer disturbances not limited to the actions taken by a customer or user of the product. Thus, it is well in line with defining the quality loss as losses to society. However, later labels used to describe noise factor categories have in a way become narrower in scope (see Table 2). The broad label of "outer disturbances" has been interpreted, or re-phrased, as for example variations in condition of use [27], "customer duty cycles" or "external environmental conditions induced by climate conditions and road inputs" [26]. The latter examples show a change of interpretation from society at large to a customer, or user, although aspects from society at large also affect the product such as e.g. the changes of legislations and regulations over time.

**Table 2. Examples of noise factor categories**

| Description of category | Taguchi (1979) [24] | Clausing (1994) [27] | Davis (2006) [26] |
|---|---|---|---|
| **Factors external to the company** | *Outer disturbances* | *Variation in condition of use* | *Customer duty cycles*<br>*External environmental conditions induced by climate conditions and road inputs* |
| **Factors internal to the company** | *Manufacturing disturbances* | *Production variation* | *Variation of part characteristic due to production conditions*<br>*Internal environmental conditions caused by complexity-induced interactions of neighboring components* |
| **Variation with time** | *Inner disturbances* | *Deterioration* | *Variation of part characteristic over time in the field* |

### 4.3 Off-line versus On-line Quality Control

Efforts for quality control are often divided into two categories based on the point in a product life cycle when they are applied [4]. On-line efforts are applied during production and off-line efforts in the design of products and manufacturing processes. On-line and off-line efforts can also be related to their ability to reduce variation [4]. In summary, the chances of decreasing the influence of noise factors increase if the efforts are applied off-line (see Table 3).

**Table 3. Development stages at which countermeasures against various categories of noise can be built into the design, adapted from [28]**

| **Development Stages** | **Category of Noise Factor** | | |
|---|---|---|---|
| | Variation in Conditions of Use | Production Variations | Deterioration |
| Product Design | X | X | X |
| Process Design | | X | |
| Manufacturing | | X | |

X = *Countermeasure possible*

Many authors, such as [23], [29], [30], and [31], emphasize the importance of applying robust design efforts proactively in the design of products and processes. Despite this emphasis in the literature, some research [32] discovered that less than half of the companies in their study used robust design proactively. With reference to Table 3, this excludes the possibility to design a product robust to variations in conditions of use and deterioration.

## 5. Analysis

The results of using the house of quality to map the SPD components into the RDM strategies can be seen in Figure 2. Five SPD components, as explained in Section 3, were used to represent the main SPD components. Three RDM strategies were chosen from the RDM literature as described in Section 4. A scale of 1, 3, 9, to denote weak, moderate, and strong relationship, respectively, was used to represent the strength of the relationship [11]. Note that at the right wing of the HoQ, six daily life examples were used to illustrate the relationships in the respective rows. For example, the cell-phone example, which is marked by an 'X' in the last row, is used to illustrate how the 'material use optimization' is related to 'noise factor identification' and 'offline robust design quality'.

| SPD components \ RDM strategies | Noise factor identification | Offline robust design quality | Minimize deviation from target | Cell-phone | Cell-phone casing | Steel bar | Water tap | Tissue dispenser | Personal Computer |
|---|---|---|---|---|---|---|---|---|---|
| Material use optimization | 1 | 1 | | | X | | | | |
| Clean Manufacturing | 9 | 9 | 9 | | | X | | | |
| Efficient distribution | 3 | 1 | | | | | | | X |
| Clean use/operation | 9 | 9 | 9 | | | | X | X | |
| End of life optimization | 3 | 9 | | X | | | | | |
| **Normalized weights** | 35% | 40% | 25% | | | | | | |
| **Rank** | 2 | 1 | 3 | | | | | | |

**Figure 2. Mapping of SPD components into RDM strategy using House of Quality**

The six daily life examples which were used to support the judgments for the interrelationships between the SPD components and RDM strategies are described as follows. It shall be noted that the examples are not exhaustive; other relevant examples may be used.

- Cell-phone: Cell phones are often disposed or exchanged before the end of their lives for keeping up with the current trend or new customer preference. Their components must be designed to withstand use, such as the user's way of handling the product, drop hazard, surrounding temperatures, or dust and dirt. If those noise factors can be identified early in the design stage (offline), the cell phones can be more durable, thus enabling design for remanufacturing or recycling. Furthermore, the modular design of the cell phones may also contribute to design for disassembly at the end of life.
- Cell-phone casing: Cell phones are commonly subjected to drop hazard, for example, where it slips off the hands of the users or dropped by children while playing. Cell phone manufacturers, therefore, must consider casings which are robust to drop hazard. One possible way to address this is by designing a thick casing

which is able to absorb the impact of the fall while not causing any damage. This in turn, increases the cost of material to be used in the production of the casings. By applying robust design strategy such as noise factor identification, in this case drop hazard, the casing could be designed using material with appropriate impact absorption capability in order to produce robust casings able to withstand the impact, without increasing material consumption.

- Steel bar: In the manufacturing of certain steel bars with a required drilling process for a hole at one end of the bar, operators' skills during positioning of steel bars for drilling are identified as the noise factor. The positioning of the drill hole is not always accurate due to differences in the judgment of different operators. To address this noise factor, a jig was designed in order to position the steel bar for accurate drilling process, regardless of the operator. The use of such a jig may therefore minimize scrap due to inaccurate drilling.
- Water tap: A water tap should be designed in such a way that it enables minimal consumption while satisfying user's needs. Not every user can close the water tap perfectly tight every time. The design of the handle with up and down movement, rather than twisting, may be seen as a more robust way towards variation in use. A water tap filter, which can disperse the water flow, for water saving can be seen as an alternative for minimal consumption.
- Tissue dispenser: A common tissue dispenser in toilets is designed with an opening at the bottom of the dispenser for users to pull the tissues for use. It is common practice that often more than one layer of tissue is dispensed when it is pulled, especially with wet hands. This is considered as a noise factor, the variation in user strength while extracting the tissue, or the wetness of user hands. In order to ensure clean use or operation of the tissue dispenser by not dispensing more tissues than needed (creating waste), the opening of the dispenser could be designed to expose the edge of the tissue rather than the whole surface. This may allow for dispensing of one layer per extraction, and therefore minimizing wastage.
- Personal computer: It is common to use various sizes and shapes of Styrofoam protections to protect the computers in carton boxes from collision during transport and distribution (noise factor). By understanding the noise factor better, for example, how the personal computers are transported and distributed, a thinner cover of shock absorbers can be designed to protect the personal computers. Thus, it may minimize the size of the packaging and increase distribution efficiency.

The findings from Figure 2 can be summarized as follows:

- Two rows, namely, 'clean manufacturing' and 'clean use or operation' received the highest points (all '9') with respect to the RDM strategies. This is not surprising because robust design techniques are generally applied for minimizing waste during manufacturing and for designing durable products or creating effective use by minimizing consumption.
- The relationship between 'material use optimization' and RDM strategies seem to be weak. This is because traditional RDM is seldom used for material selection. There is a need to broaden the boundary of RDM use.
- In some cases, there is a blank in the relationship. This implies that there is no relationship between the two. For example, there is no relationship between 'efficient distribution' and 'minimize deviation from target'. This is because the focus of RDM is more on the product, rather than on the supply chains.
- If one wants to rank the importance of the three RDM strategies, then the 'offline robust design quality', which implies the importance of doing robust design upstream, receive the highest rank followed by 'noise factor identification' and 'minimize deviation from target'. Note that the importance percentages were computed by normalizing the sum of all numbers column-wise.
- In the roof of the house, it is indicated that all the three RDM are strongly related in a positive way. This means enhancement in one strategy can positively enhance the others. For example, good noise factor identification will positively contribute to minimizing deviation from target simply because it provides information on the causes of deviation.

## 6. Discussion and Conclusions

As stated by Luttropp and Lagerstedt [6] and Maxwell and Van der Vorst [7], a way forward in the area of SPD is to integrate sustainability aspects in already existing engineering methods. In line with this, the purpose of this paper was to explore the likely contributions of RDM strategies to SPD, and to propose a research agenda for developing the area of sustainable robust design. This section will first discuss the findings from the HoQ as summarized in the preceding section. It is concluded by a proposal of an agenda for future research that can contribute to developing RDM in ways that are supportive of sustainability.

The link between RDM and SPD appears strongest in the area of 'clean manufacturing' and 'clean use or operation'. This can probably be attributed to the fact that the focus of the majority of RDM efforts in organizations are not upstream [32], hence the parts most elaborated on are related to manufacturing. However, there is a broad agreement on the need to apply RDM upstream (e.g. [23], [21], and [31]). Furthermore, in the area of sustainability, the focus is shifting from end-of-life to a view of continuous applicability during product development [18]. As both areas are in stages where practices and tools for upstream efforts are in need, integration of sustainability aspects in upstream RDM practices could be valuable. One example could be to have an explicit focus on environmental effects in the P-diagram when applied in concept stages for robustness analysis. This would also require a broadened view on noise factors, focusing on society at large, to some extent moving back to and refine the original categorization by Taguchi [24].

RDM is an engineering methodology that in its history has a strong link to sustainability through the definition of quality loss and its focus on losses to the society at large [4]; one such loss being environmental damages [22]. Over the years main focus has, however, been on loss to the customer. In line with the current need for a focus on sustainability, in society at large as well as in the area of product development [12], it is time to go back to the original focus of quality loss. This means that the RDM efforts should focus not only on minimizing unwanted variation in the output experienced by the customer, but also a minimization of, for example, environmental damages. This will call for a need of a broadened view from the 'now, here, and individual' to 'now and in the future, a systemic view, and society at large'. In conclusion, we therefore suggest some areas of future research as summarized in Table 4 below.

**Table 4. Proposed definition of sustainable RDM components**

| Concept | Traditional RDM | Sustainable RDM |
|---|---|---|
| Minimize deviation from target | Loss to society, in practice often limited to loss to customer | Loss to society and environment |
| Noise factor definition | Variation in conditions of use, production variation, deterioration | As traditional but expanded to include aspects such as customer lifestyle and convenience. |
| Offline robust design | Upstream quality control | Upstream quality control with product lifecycle analysis |
| Response variable | Mean and variance | Mean, variance, and sustainability indicators |

First, as argued earlier the view on quality loss has to be expanded to reclaim the focus on society at large, and research is needed into how this view can be operationalized and put into practice. An example is how to integrate the material use aspect, e.g. use of hazardous material, as a consideration when evaluating robustness. Second, the broadened view has consequences on the noise factor definition and identification, where additions to capture aspects like variation in customers' environmental awareness should be taken into account. Third, research on how to integrate lifecycle analysis and RDM is an area of interest for future research. Finally, from a more operational point of view, the use of RDM should consider the sustainability indicators (e.g. $CO_2$ emission) in addition to the mean and variance of the response variable. In other words, it calls for multiple responses optimization approach in which the best compromise should be sought.

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