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Research

Principles of Robust Design Methodology

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The literature on robust design has focused chiefly on the development of methods for identifying robust design solutions. In this paper we present a literature review of conflicts and agreements on the principles of robust design. Through this review four central principles of robust design are identified: awareness of variation, insensitivity to noise factors, application of various methods, and application in all stages of a design process. These principles are comprised into the following definition of robust design methodology: Robust design methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product design. Copyright © 2007 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Much has happened since Nair[1] published a panel discussion on Taguchi's parameter design and robust design. Robust design in this sense refers to designing products so that they are insensitive to variation. Robinson *et al.*[2] give an update on developments since 1992, concentrating on the use of statistical methods to achieve robust designs. An overview of different methods to achieve robust designs is also provided by Park *et al.*[3]. However, most papers on robust design do not have their main focus on the concept of robust design and its underlying principles. The purpose of this work is to investigate the principles of robust design in a literature review; principles that are not associated with specific methods but capture an underlying way of thinking.

The importance of reducing variation in product characteristics was discussed early in Japan. The ideas of Japanese engineer Genichi Taguchi were already known in his own country in the 1940s

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(Gunter[4]), although they did not receive international attention until the 1980s when they were published in English. In 1979, Taguchi's ideas were translated in Taguchi and Wu[5], a publication that was followed by many others on the subject, see e.g. Taguchi[6], Phadke[7], Taguchi *et al.*[8]. Taguchi[6] proposes a three-step strategy for the development of products. The steps are system design, parameter design and tolerance design, with an emphasis on the use of experimental methods in the latter two steps.

The papers by Hunter[9] and Kackar[10] explained the essence of Taguchi's ideas in an understandable and comprehensive manner. In the late 1980s and beginning of the 1990s there was discussion on the appropriateness of the statistical methods proposed by Taguchi. Publications contributing to this discussion were León *et al.*[11], Box *et al.*[12], Shainin and Shainin[13], Welch *et al.*[14], Shoemaker *et al.*[15], Box and Jones[16], Nair[1], Lucas[17], and Grize[18]. There are fewer publications that focus mainly on non-statistical issues such as principles, procedures, and objectives.

This paper starts with a description of the literature search. An analysis section deals with terminology, views of variation, various procedures that can be used to achieve robust design, the objective of robust design, methods and methodologies, and the experimental approaches that are advocated. In a synthesis of the analysis we identify a number of principles and provide a definition of robust design methodology (RDM). The final section contains a discussion and ideas for future research.

2. METHOD

The literature has been identified through searches in Dissertation Abstracts and in three databases, Compendex, Science Citation Index and EBSCO Host, including Academic Search Elite and Business Source Elite. In all databases, searches were made in titles, abstracts or topic descriptions for the following key words: RDM, robust design, Taguchi method, quality engineering and robust engineering. The selection of papers found in the databases was done in two steps—first based on title, source and author/s and second on abstract. The selection criteria were derived from the purpose of investigating principles of robust design, i.e. not chiefly focusing on statistical methods useful in robust design. The final number of papers identified in the database searches is given in Table I.

In Table I a reference is counted only once, even if it was found in multiple databases. In addition to the database searches, book searches have been made in the Swedish national catalogue Libris and the catalogue of Oxford University Library. The initial search was conducted in November 2003 and complementary searches have been conducted up to November 2006. In addition to these searches, literature was found by following citations in papers and books. From this literature a number of recurring and central aspects of robust design were identified.

Table I. Summary of the database searches

	Database			
Search item	Dissertation abstracts	Compendex	Science citation index	EBSCO
Robust design methodology	**2** (16)	**2** (37)	**2** (28)	**3** (7)
Robust design	**3** (178)	**16** (1156)	**26** (797)	**17** (151)
Taguchi method	**2** (53)	**9** (684)	**8** (563)	**8** (82)
Quality engineering	**0** (39)	**7** (385)	**5** (162)	**5** (96)
Robust engineering	**0** (4)	**0** (27)	**0** (7)	**0** (2)

Note: Bold figures are the number of selected papers per search item and database; figures in parentheses are the number of hits before any selection.

3. RESULTS AND ANALYSIS

3.1. Terminology

The concepts used to describe efforts to reduce variation in product characteristics are many; some examples are *Taguchi methods*, *quality engineering*, *parameter design*, *robust design*, *robust engineering*, and *RDM*. As seen in Table I, *robust design* is the most common terminology in databases containing papers and dissertations, followed by *Taguchi methods*. Moreover, textbooks on Taguchi methods are quite common, however, they are not included in the table as they were found in book searches.

The concept of *quality engineering* appears in publications such as Taguchi and Wu[5], Taguchi[6,19], and Saitoh *et al.*[20,21]. Taguchi[19] writes that '*quality engineering is not intended to reduce the sources of variation in products directly. Instead, one needs to make the systems of products or production processes less sensitive to sources of uncontrollable noise, or outside influences, through parameter design (off-line quality control) methods*.' In the literature, *quality engineering* encompasses the concepts of system design, parameter design, and tolerance design. These concepts are often labeled *Taguchi methods* or *Taguchi techniques*, see Roy[22], Benton[23], Ross[24], and Wu and Wu[25].

In addition to the concepts dealt with so far there are a number of concepts that are more general than those that indicate a connection to the work of Taguchi, e.g. *robustness*, *robust design*, and *RDM*. These are used in e.g. Goh[26], Matthiasen[27], Andersson[28], Thornton *et al.*[29], Box[30], Gremyr *et al.*[31], and Thornton[32]. These concepts are referred to as general because they do not, in the same way as the concepts related to Taguchi, prescribe specific methods for reducing variation. Rather, they are used when robustness is seen as an engineering problem that can be solved in a number of ways. *A robust design* is of course also used as a description of a characteristic of a product. This characteristic of being robust has simply to do with insensitivity to variation; for discussions and elaborations see Hoehn[33], Ford[34], and Andersson[28].

3.2. View of variation

Although many authors—for example, Tribus and Szonyi[35], Pignatiello and Ramberg [36] and the contributors in Nair[1]—are critical to the statistical methods advocated by Taguchi, they give him credit for his work on communicating the importance of reducing variation to industry. As Lorenzen writes in Nair[1] '*... there is certainly no doubt that Taguchi has popularised the idea of robustness within the engineering community, and this is a big contribution*.' This points to a common base in the literature on robust design, the view that variation is a fundamental problem, as stated in Goh[37]: '*Regardless of the physical criteria used as proxy to quality and the way in which specifications are arrived at, all quality problems during generation of goods and services arise fundamentally from only one source: variation*.' Similarly, Box and Bisgaard[38] write '*the enemy of mass production is variability. Success in reducing it will invariably simplify processes, reduce scrap, and lower costs*.'

3.2.1. The quadratic loss function

Taguchi and Wu[5] define quality as '*the losses a product imparts to the society from the time the product is shipped*'. These losses fall under two categories: loss caused by functional variation and loss caused by harmful side effects. Kackar[39] questions the definition of quality given above for neglecting losses before a product is shipped, e.g. scrap in manufacturing, and suggests an extension of the definition to include manufacturing loss as well.

A central illustration of the concept of loss used in e.g., Taguchi and Wu[5], Roy[22], and Ross[24] is the quadratic loss function, an illustration that Benton[23] refers to as 'the heart of the Taguchi philosophy'. A criticism of loss functions, see Matthiasen[27] and Box *et al.*[12], is that it is a good illustration but not actually useful owing to the difficulties of characterizing and balancing economic loss. However, Bergman and Klefsjö[40] refer to a practical case at General Motors where the quality loss function was estimated through customer ranking of unsatisfactory and satisfactory levels of a certain parameter.

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3.2.2. Noise factors

The forces that cause deviation from target and thus induce loss are often labelled noise, noise factors or simply sources of variation, see e.g., Taguchi[6], Park[41], Ross[24], and Wu and Wu[25]. Many authors divide noise factors into different categories as a means to clarify the kinds of noise that can induce loss, see e.g. Taguchi and Wu[5], Taguchi[6], Clausing[42], and Phadke[7]. There are most often three categories, the names used for these categories are different but the content of them is very similar. Examples of categories are external noise, internal noise and unit-to-unit noise as proposed in Taguchi[6] or, as suggested by Clausing[42], variations in conditions of use, production variations and deterioration (variation with time and use).

Besides inducing loss, noise factors are difficult, expensive or even impossible to control. As stated in e.g. Gunter[4], Phadke[7], and Park[41], noise factors cannot be easily or cost effectively controlled, which makes insensitivity to noise factors rather than elimination of them the preferable way to achieve a robust design. The final aim, i.e. robustness, is defined in Taguchi *et al.*[8] as '*the state where the technology*, *product*, *or process performance is minimally sensitive to factors causing variability* (*either in manufacturing or user*'*s environment*) *and aging at the lowest manufacturing cost*.' In other words, the aim is not to eliminate noise but to create insensitivity to it. This can be done either by identifying levels of control factors that result in a more robust product; or in some cases even by re-design of the product.

3.3. Procedures

3.3.1. A specific procedure or an overall approach

Looking briefly at parts of the literature on robust design it is tempting to believe that robust design is synonymous with the three-step procedure proposed by Taguchi[6] and that it implies the use of designed experiments. This view is illustrated by the following quote from Tsui[43]: '*robust design is an efficient and systematic methodology that applies statistical experimental design for improving product and manufacturing process design. … The robust design method was originally developed by a Japanese quality consultant*, *Genichi Taguchi*.' Shoemaker and Tsui express another view in Nair[1] '*It should be emphasized that robust design is a problem in product design and manufacturing-process design and that it does not imply any specific solution methods*.' The intriguing fact that both these illustrative quotes were taken from the same author in the same year might indicate a certain level of inattention to the concept of robust design.

Mörup[44], Thornton *et al.*[29], and Tennant[45] consider robust design to be an overall approach and Shoemaker and Tsui in Nair[1] consider robust design as 'a problem' in engineering. A difference between authors who consider robust design to be a specific procedure and those who view it as an overall approach concerns the concept or system design phase. Andersson[46] says that the development of robust designs may be enhanced by appropriate choices of concepts, which, in Taguchi's terminology, is a part of system design. Andersson[46] further argues that a wise choice of concept is the only possible option for achieving robust design in situations in which physical experimentation or computer simulations are impossible. Examples of methods proposed by Andersson[46–48] are an adapted failure mode and effect analysis, which take into account the influence of noise factors, the use of the error transmission formula to evaluate different design solutions and the use of design rules and principles that contribute to robust design. Another author that deals with robustness in system design is Goh[26]. His proposal is to simulate environmental variables in the design stage to expose possible weaknesses in a product or process. Taguchi[19] on the other hand argues that robust design is not dependent to any great extent on work in the system design phase.

The view of robust design as a specific procedure is supported in Lin *et al.*[49] and Chowdhury[50]. Here robust design is seen as identical to the application of a designed experiment analyzed by signal-to-noise ratios as a means of finding a robust solution. In Chowdhury[50] robust design is applied as a subordinate part of the overall framework Design for Six Sigma (DFSS). In this case robust design is seen as a synonym of the Taguchi[6] three-step procedure with a focus on the use of design of experiments in parameter design.

3.3.2. Taguchi's three-step procedure

The design process described in Taguchi and Wu [5] and Taguchi[6,51] is strongly associated with the concept of quality engineering, see e.g. Ramberg *et al.*[52] and Goh[26]. According to the description in Taguchi[6], system

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Table II. Off-line and on-line quality control as countermeasures against noise (Taguchi[6])

	Department	Countermeasures	Type of noise: External	Internal	Unit-to-unit
Off-line quality control	R&D	(1) System design	•	•	•
		(2) Parameter design	•	•	•
		(3) Tolerance design	∘	•	•
	Production engineering	(1) System design	×	×	•
		(2) Parameter design	×	×	•
		(3) Tolerance design	×	×	•
On-line quality control	Production	(1) System design	×	×	•
		(2) Parameter design	×	×	•
		(3) Tolerance design	×	×	•
	Customer relations	After-sales service	×	×	×

Note: •, possible; ∘, possible, but should be a last resort; ×, impossible.

design is the stage in which different concepts and choices of technology are considered at different levels, e.g. the system level and component level. The aim in parameter design is to decide on appropriate levels of individual system parameters. What is an appropriate level for a parameter or an appropriate combination of parameter levels is determined by what reduces the effect of noise on the output characteristic. Finally, in the last step, tolerances are set in a way that further minimizes the effect of noise, e.g. narrower tolerances for noise factors that have the greatest influence. Taguchi[6] emphasizes, however, that this is not the most efficient way to reduce variation caused by noise and that it should be seen as a last resort after parameter design.

Work to achieve robustness is divided in Taguchi and Wu[5] into off-line and on-line quality control efforts, where the former is applied during the design of a product and the latter during production. The different approaches vary in their ability to create robustness against different categories of noise factors. The focus in this paper is what Taguchi refers to as off-line quality control effort. In many references, e.g. Taguchi[6,53], Kackar[10], and Phadke[7], on-line and off-line quality control are related to categories of noise factors in tables similar to Table II.

The major means of achieving a robust design according to Taguchi[6] is through parameter design; thus it is less important to think about robustness in system design. Lin *et al.*[49] say that Taguchi methods are useful from the beginning of research and development to the end of the production line, but system design is left out in their list of activities. Another example of the focus on parameter design is in Chan and Xiao[54], who view robust design and parameter design as synonymous. Benton[23] summarizes this by saying '*System design…In this phase Taguchi methods offer little help*.' The emphasis on the latter phases of product design is not uncontroversial, as can be seen in Ford[34]: '*the traditional approaches to robust design are limited to optimisation of design parameter values and neglect opportunities at the concept definition stage*.' Andersson[46] argues that Taguchi overemphasizes parameter design as the only option for achieving robust designs. Such authors as Dabade and Ray[55] and Wilkins[56] also seem to have interpreted his work in this way.

3.4. Objective

While there is a common aim of reducing unwanted variation, there is controversy in the more long-term aims of these efforts. Parr[57] describes this as two approaches toward robust design: one solution oriented and another understanding oriented. Lin *et al.*[49] illustrate the difference between these approaches: '*The difference between statistical methods and Taguchi methods is that statistical methods tell you what has happened and Taguchi methods tell you how to make it happen*.'

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The notion of a solution-oriented and an understanding-oriented approach to robust design is described in some of the literature on robust design as an issue of engineering versus science. A statement that clearly illustrates the solution-oriented view is found in Nair[1] where Shin Taguchi states: '*The goal in parameter design is not to characterize the system but to achieve robust function. Pure science strives to discover the causal relationships and to understand the mechanics of how things happen. Engineering*, *however*, *strives to achieve the results needed to satisfy the customer. Moreover*, *cost and time are very important issues for engineers. Science is to explain nature while engineering is to utilize nature*.' Taguchi[19] and Taguchi *et al.*[8] have similar views.

George Box responds to Shin Taguchi in the panel discussion in Nair[1]: '*… the ultimate goal must surely be to better understand the engineering system. … I profoundly disagree with the implications of Shin Taguchi's claim that the engineer does not need to* '*discover the causal relationship and to understand the mechanics of how things happen*'.' Other authors that emphasize the understanding of the system under study are Box and Bisgaard[38], Tsui[58], Scibilia *et al.*[59], and Smith and Clarkson[60]. The understanding- versus solution-oriented approach to robust design is also reflected in the use of experimental designs. Pignatiello and Ramberg[36] and Goh[26] criticize Taguchi for reducing the use of experimental design to a set of 'cookbook' procedures that give no explanations of 'why?' and 'how?'.

3.5. Methods and methodologies

Numerous methods have been developed to support the design of robust products. The majority focus on design improvement and only a limited number have been proposed as an aid to support robust design in what Taguchi[6] refers to as system design. However, Thornton[32] proposes a methodology called variation risk management (VRM) that is intended to be incorporated in a product development process. According to Thornton[32], VRM can serve as an overall framework for reducing variation from system design to production.

Johansson *et al.*[61] describe a method for variation reduction that is applicable in the concept selection phase as well as in improving existing designs. They call the method variation mode and effects analysis (VMEA) and maintain that it is useful for identifying noise factors that influence a design. Further, Andersson[46] suggests a semi-analytic approach based on the error transmission formula (see e.g. Morrison[62]) that may serve as an aid in comparisons of the sensitivity to noise factors in different designs. Matthiasen[27] and Andersson[48] suggest the use of design principles as a means of imposing robust design in system design phases. Another method for robust design in the concept stages of development is the robust concept design method developed by Ford[34]. This consists of four steps: defining the robustness problem, deriving guiding principles, making a new concept synthesis and evaluating alternative concepts.

Interest in robust design, and particularly robust design experimentation, increased in the US and in Europe in the 1980s, partly owing to the publishing of Taguchi and Wu[5]. Taguchi and Wu[5] advocate the use of orthogonal arrays where both control factors and noise factors are varied. These experiments are analyzed by the use of signal-to-noise ratios to identify robust designs. The rationale behind the signal-to-noise ratios is that they are linked to the quadratic loss function. Maghsoodloo[63] explores the exact relation between some of the most commonly used signal-to-noise ratios and the quadratic loss function.

The essence of Taguchi's ideas on the use of design of experiments to improve designs was explained by Kackar[10] and Hunter[9]. A large number of papers have been published on the use of design of experiments to identify robust designs, and a recent review by Robinson *et al.*[2] summarizes the central points of the research in this area. However, as Li *et al.*[64] point out, there is a need of more work on other methods than design of experiments in the parameter design phase. Examples are the use of smart assemblies described in Downey *et al.*[65], standardization of parts as a means of withstanding production variations outlined in Little and Singh[66], and the integration of a product family concept and robust design suggested in Sopadang[67].

It is impossible or too expensive in some cases to conduct physical experiments. In such situations it can instead be possible to build simulation models that take into account both control factors and noise factors, see Welch *et al.*[14], Benjamin *et al.*[68], Ramberg *et al.*[52], Barone and Lanzotti[69], Jeang and Chang[70], and Creighton and Nahavandi[71]. The influence of noise factors on the system can be investigated in appropriately planned computer experiments.

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When variation cannot be brought to a satisfactory level by wisely selected control factor levels, Taguchi and Wu[5] argue that it should be minimized by controlling the noise factors. Taguchi[6] writes that choosing the noise factors to control should be based on the associated cost and their contribution to the total amount of variation. Nigam and Turner[72] present a review of statistically based methods for studying how variation caused by different noise factors propagates to the total variation. Bisgaard and Ankenman[73] argue that the Taguchi two-step strategy of first seeking appropriate control factor settings and then, when needed, controlling certain noise factors may lead to non-optimal solutions. Chan and Xiao[54] and Li and Wu[74] integrate these two steps for reducing variation.

3.6. *Experimental approach*

The core of Taguchi's parameter design is based on experimental methods. Since the beginning of the 1980s there has been ongoing research to suggest alternatives and improvements of the methods he suggested. Useful references to obtain a picture of the current status of robust parameter design (RPD) are Wu and Hamada[75], Myers and Montgomery[76], Robinson *et al.*[2], and Myers *et al.*[77].

3.6.1. *Suitable experimental designs*

The basic idea of RPD experiments is to vary control factors and noise factors in the same experiment and seek possible control–noise factor interactions. The combined array approach suggested by Welch *et al.*[14] and Shoemaker *et al.*[15] includes noise factors and control factors in the same design matrix, which often results in cost-efficient experiments. Moreover, by use of mixed resolution designs suggested by Lucas[78], experiments can be designed with high resolution for control–noise factor interactions and control–control factor interactions while having lower resolution for noise–noise factor interactions. Lucas[17] proposed the use of response surface designs with mixed resolution and emphasized their superiority over the experimental designs advocated by Taguchi. Borkowski and Lucas[79] continued the work in Lucas[17] and developed a catalogue of mixed resolution response surface designs.

Another resource efficient experimental arrangement is split-plot experiments where the experimental order is not completely randomized and all factor levels are not reset between each experiment, see Box and Jones[16], Letsinger *et al.*[80], and Bisgaard[81]. Another positive characteristic of these experiments is that they allow a precise estimation of control–noise factor interactions. Bisgaard[81] showed how the mixed resolution concept can be applied also to split-plot experiments. The use and usefulness of split-plot designs in RPD have been discussed by Kowalski[82], Loeppky *et al.*[83], Bingham and Sitter[84,85] and McLeod and Brewster[86].

Borror *et al.*[87] evaluated design matrices for RPD with respect to two different variance criteria. Other recent references suggesting design evaluation criteria are Bingham and Li[88] and Loeppky *et al.*[89].

3.6.2. *Different approaches to analysis*

Robinson *et al.*[2] and Myers *et al.*[77] discuss the two response surface methodology (RSM) approaches that evolved during the 1990s to analyze robust design problems: the single and the dual response approach. In the dual model approach, originally proposed by Vining and Myers[90], separate models are fitted for the mean and the variance. This type of analysis requires replicated experiments or the inner–outer arrays type experiments often advocated by Taguchi[6]. In the single response approach originally proposed by Welch *et al.*[14], control factors and noise factors coexist in the same model. Myers *et al.*[91] pointed out that two response surfaces, one for the mean and one for the variance, can be determined theoretically from the single response model. The two models are further considered jointly to identify the best choice of control factor settings. Steinberg and Bursztyn[92] compared the single and dual response approaches and showed that the single response approach is favourable if noise factors have been controlled at fixed levels in experiments.

Lee and Nelder[93] proposed a generalized linear model (GLM) approach when common assumptions made in RSM are not justified. Engel and Huele[94] proposed a GLM for situations where the residual variance cannot be assumed to be constant. Myers *et al.*[95] suggested a GLM approach for the analysis of RPD experiments with non-normal responses. Robinson *et al.*[96] extended the analysis to experiments with random

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noise variables and non-normal responses, in this case generalized linear mixed models should be used as GLMs require independent responses.

Brenneman and Myers[97] investigated the situation when categorical noise factors, as e.g. different performance of production equipment or different suppliers, are varied in RPD experiments. Under the assumption that the proportions of each category of the noise factors are known, an analysis procedure was proposed. Moreover, Brenneman and Myers[97] implied that process variance can be reduced by utilizing not only possible control–noise factor interactions but also by adjusting the proportions of the categories of the noise factors. Robinson *et al.*[98] continued the work of Brenneman and Myers[97] and proposed an analysis strategy taking into account the possibility to make adjustments of the category proportions and the cost or suitability associated with different control factor settings.

The experimental designs and analyses procedures dealt with in this section are all based on explicit modelling of the response and aimed at increasing the understanding of the problem under study. In other words, current research on robust design is in line with the understanding-oriented approach rather than the solution-oriented approach (see Section 3.4).

4. CONCLUSIONS

4.1. Synthesis

Despite all the debates on the practical use of the quality loss function the most fundamental common denominator in the literature on robustness and robust design is that unwanted variation imparts loss. This loss is induced by noise factors that are often hard or impossible to control in an affordable way. These factors can arise in the conditions of use or in production or be caused by deterioration. Due to the nature of noise factors the aim of robust design is to create insensitivity to them rather than to try to eliminate or control them.

A more controversial area is the approaches for achieving robust design. For some authors robust design is a general problem, whereas others see it as synonymous to Taguchi's three-step procedure. Further, there is disagreement on the value of robust design efforts in the development and selection of concepts, where some argue that it is crucial to apply robust design as early as possible, whereas others feel that it is applicable mainly in the realization of a chosen concept.

There is no conflict over design of experiments being useful in robust design; the way in which these experiments should be conducted and analyzed, however, is the greatest point of conflict in the literature on robust design. It concerns various factors, such as resource efficiency, view on interactions, signal-to-noise ratios, and one shot versus sequential experimentation. The latter aspect is also closely connected to another controversy: whether the goal of robust design is to arrive at one robust solution or whether it is also a matter of understanding the underlying causes of variation. Finally, despite the many controversies over the statistically based methods advocated by Taguchi, there is broad agreement on the value of Taguchi's contribution in emphasizing variation reduction and creating industrial interest in it.

4.2. A definition of robust design methodology

This examination of the literature review raises a fundamental question: what is robust design? It is apparent from the sections above that this question has many different answers. Below we will give our answer.

First, a cornerstone of robust design is an awareness of variation. Talking about products, there is a view in which the product is not only affected by controllable factors but also by factors that are uncontrollable or hard to control. The latter factors are referred to as noise factors, which cause a characteristic to deviate from its desired and/or specified level. To this time most research on variation reduction has focused on method development rather than on increasing and emphasizing the awareness of variation. This focus might be one factor underlying the low level of industrial applications of robust design, as reported in

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Gremyr *et al.*[31]. Further, there would probably be a better understanding of the methods that have been developed if the underlying views on variation were better articulated.

Secondly, the nature of noise factors as being impossible or expensive to control often makes robustness by means of control or elimination of these factors an unappealing approach. The goal in robust design is rather to create insensitivity to noise factors.

Thirdly, we argue that robust design does not in itself prescribe the use of certain methods applied in specified steps. This should not be interpreted, however, as though it only has to do with creating a robust product in any possible way by making it stronger and heavier, but through insensitivity to, and awareness of, noise factors. To stress this we would like to use the concept of RDM. Methodology is defined in the Oxford English Dictionary as '*a method or body of methods used in a particular field of study or activity*'. In our view the field of RDM is based on a number of underlying models: a product as being affected by controllable factors as well as noise factors, the quality loss function showing that unwanted variation induces loss, and the view that it is important to create insensitivity to all categories of noise factors and to apply such efforts from system design to production. With this base a number of different methods, not necessarily design of experiments although useful, can be applied to arrive at a robust design. An advantage of using RDM rather than robust design to describe efforts toward robustness is that it distinguishes the methodology from a characteristic. In other words, it clarifies that a product can be robust with or without the application of RDM.

Fourthly, RDM is useful from concept generation to the production of a product. Moreover, it is necessary to apply RDM throughout a development process in order to exploit all possibilities for robustness covering all categories of noise factors.

The four key areas of RDM can be summarized in the following definition:

Robust design methodology means systematic efforts to achieve insensitivity to noise factors. These efforts are founded on an awareness of variation and can be applied in all stages of product design.

5. DISCUSSION

It is clear from the literature reviewed in this paper that there are many, almost synonymous concepts that are used to describe efforts to achieve robust designs. However, there is agreement on some fundamental principles among the users of different concepts. This common ground can be found in the view of variation and the emphasis on insensitivity to, rather than elimination of, noise factors. It is shown in Gremyr *et al.*[31] that practitioners also recognize variation as a problematic issue. Thus, it is important to further investigate why the research conducted on robust design does not seem to meet this industrial need.

A survey of Swedish manufacturing companies presented in Arvidsson *et al.*[99] and Gremyr *et al.*[31] shows that as few as 28% of the companies in that study recognize the concept of robust design despite the fact that the area has received considerable interest in journals and textbooks. In a related study, discussed in Gremyr and Johansson[100], industrial users of robust design emphasized the need for support in applying RDM. Taking these studies into consideration the inattention to the framework of RDM in favor of research on applicable statistical methods might have contributed to the low level of industrial use.

The study of the literature treated in this paper brings out the importance of reflecting upon a number of specific areas that have yet received little or no attention. One is the implementation of RDM. How should a company that wants to start working with RDM proceed? One publication that is related to this topic is Saitoh *et al.*[20,21], which describes how quality engineering has been implemented in Fuji Zerox in Japan. Concerning the ideas in robust design that have their origin in Japan, one thing that must be considered when taking it to a western company is, as discussed in Goh[26], cultural differences. Another aspect of implementation is the organization of robust design work; should it be run in individual projects or as an integrated part of a company's development process? Finally, it seems that efforts are needed in developing methods that support awareness of variation in early design phases, e.g. in concepts generation.

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