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A CLASSIFICATION OF THE INDUSTRIAL RELEVANCE OF ROBUST DESIGN METHODS

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ABSTRACT

The use of Robust Design Methods in industry is limited. Based on statements from industrial surveys and the authors' experience from working with industrial design in industry, it is suggested that the barriers for industrial implementation of RDM is the lack of early-stage methods that can provide the design team with leading and quantifiable metrics in a simple and fast manner.

Using this assumption, success criteria for the implementation of RDM in industry and a classification of the current body of robust design methods are presented. The presented classifications show that only a limited number of methods focus on the reduction on sensitivity to variation and that especially in early design stages, there are almost no leading and quantitative methods available. Existing methods most often rely on data from previous projects and the experience of the design team.

It is concluded, that the low use of RDM in industrial practice can be explained by the lack of operational tools to fulfill the existing Robust Design principles. Consequently, a suitable framework with leading, early-stage, and quantitative methods and metrics must be developed.

Keywords: robust design, reliability, kinematic design, sensitivity, variation

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1 INTRODUCTION

Robust Design Methods (RDM) comprises a set of principles, tools, and metrics that are used to analyze and design products such that they become insensitive to changes in their design parameters. However, surveys have shown, that industrial use of RDM is limited – not only by absolute measures, but also relatively, when compared to the use of other design methods. The purpose of this paper is to 1) identify the criteria that robust design methods need to fulfill in order to be adopted and implemented in industry and 2) to review, classify and discuss to which extent the current body of robust design methods fulfill these criteria. The result of the contribution can be used to identify shortcomings of the current state-of-the-art as well as for pointing out a direction for research and the development of new robust design methods that will become successful in industry.

2 BACKGROUND

Robust Design was first introduced in the 1950's by the Japanese engineer and statistician Genichi Taguchi and was popularized in the 1980's, where it was applied at Boeing and Ford Motor Co. among others (Taguchi et al. 2005). Initially RDM was centered on the concept of quantifying the societal loss due to variation in functional performance and on the use of experimental analysis to select values of design parameters, such that the resulting design became insensitive to changes in the design parameters. Since then, RDM has evolved into a separate research field, including a wide variety of principles and methods.

2.1 Industrial use of RDM

Although RDM literature offers a wide array of principles and methods, surveys show that the application of RDM in industry is limited. In a survey of the Swedish manufacturing industry (Gremyr et al. 2003), 80% of the respondents reply that they work actively to reduce variation between samples of the same product, but only 18% of the respondents use robust design methods, despite that the primary objective of using RDM is exactly the reduction of functional variation.

In the United Kingdom, a study by Araujo et al. (1996) on the industrial use of 31 different product development methods ranks the methods by the degree of use in industry. The list includes 4 Robust Design Methods: Robust Design (Taguchi), Fault Trees, and Design of Experiments (DOE), 3 of which are placed amongst the 4 least used methods (31, 29, and 28 respectively), whereas FMEA is placed as no. 8. This indicates that even though engineering design methods in general may have a low adaptation rate in industry, robust design methods still have a relatively lower use-rate than other methods.

Thornton et al. (2000) have conducted a survey on the use of RDM in US industry, which shows that only 39% of commercial companies "proactively use robust design", meaning that they use it throughout the design process, and that 38% use it reactively to issues that are identified during production ramp-up.

Combining the results of these surveys, it seems that the use of robust design is limited in industry – both in absolute measures and relative to other engineering design methods. Moreover, when it is used, it is often used in the late design stages to solve experienced issues rather than in the early design stages as a method for preventing issues from occurring. This raises a question regarding the barriers for applying robust design methods in industry.

2.2 Barriers for using RDM

Generally, the introduction of new processes and methods in any organization can be a challenge (Araujo 2001). The list of potential barriers is long, but can roughly be summarized as:

- **Organisational barriers:** Fear of change. Lack of organizational support. No promotion of value proposition. Methods are applied wrong. Lack of training. Lack of competence in organization.
- **Method barriers:** Methods are not applicable. Method does not create wanted effect. Efficiency of method (effect vs. time/cost to use). Poor design of method. Lack of appeal. Results are not operational/ usable.

The organizational barriers are generic and well-known. They could be relevant regardless of the method in question and can explain the general lack of usage of structured design methods in industry,

but do not specifically explain why RDM also by relative measures have not been adopted and implemented by industry. This explanation must lie within the methods themselves. In other words, there is an inherent barrier within the available robust design methods that results in the relatively low usage in industry. Several authors within RDM have criticized the methodology for various reasons.
Matthiassen (1997) and Andersson (1996) criticize RDM for not providing support in the early design stages and for having too much focus on statistics and parameter optimization rather than engineering design and support in the conceptual and architectural design phases. Thornton et al. (2000) state, that there is a *"lack of quantitative models that enable a design team to make quick and accurate decisions"* and continues by stating *"that there is large body of literature but the tools are too complex"*. Araujo et al. (1996) claim that the '*tools require experienced or trained staff*' and Gremyr et al. (2003) states that the "*major part of research on RDM has focused on developing statistical techniques*".

2.3 Industrial Success Criteria

The picture described in the previous section, of Robust Design Methods primarily being late-stage, timely to use, and with too much focus in statistics corresponds well with the authors' experience from working with industry – there is an expressed request for simple, objective methods that can be applied as design tools in highly iterative development projects, with constantly changing designs. This critique can be used, however, to describe the success criteria for RDM to be adopted by industry. What makes the popular methods from the surveys popular? What would an ideal robust design method look like, in the eyes of the industry? Based on a combination of the statements from the surveys and the authors' consulting experience, the following success criteria have been established:

1. **Leading indicators.** Many metrics are lagging, meaning that they show what *has happened*, rather than indicate what is *going to happen*. An example of a lagging indicator (sometimes referred to as 'effect indicator') in robust design, is 'production yield'. Leading indicators are preferable because they allow time for design changes. A good leading indicator is associated with a lagging/effect indicator, thereby allowing it to be used as an indicator of the effects of continuing with the current design.
2. **Quantifiable metrics.** Management and engineers want to make data-driven decisions. Therefore, they need quantifiable metrics that are easy to implement and allow for comparison with alternative solutions, previous projects, industrial standards or competitor products. This criteria is also stated by Thornton (2004)
3. **Early-stage application**. The cost of design changes increases exponentially as a development project progresses and metrics and methods that are applicable at an early-stage are therefore preferable. Real-life projects seldom follow a strict linear development process, but rather use frontloading of critical issues. In this paper, 'early-stage' is therefore not defined by the stage in which a method can be used, but rather on the necessary information needed to apply the method (e.g. sketch, architecture, dimensions, tolerances, physical models, etc).

Obviously, other aspects than the ones mentioned here, are also relevant. For example, aspects such as *required training, impact of method* and *resources required to use the method* are relevant, but are more difficult to use for categorization purposes, since they are not inherent characteristics of the method, but rather dependent on how and where the method is applied. They are therefore left out of the analysis.

3 DELIMITATION OF TERMS AND CORRESPONDING METHODS

A wide variety of approaches aiming at an improvement of product quality is available in literature. Well-known are the Failure Mode and Effects Analysis (FMEA) commonly used in the European automotive industry (Bertsche 2008; Kumamoto 2007), lifetime calculations of machine components (Bertsche 2008), or Statistical Process Control (SPC) (MacCarthy, Wasusri 2002). The basic difference between RDM and other approaches is illustrated by means of Taguchi's Quality Loss Function in Figure 1. Traditionally, quality control methods focus on the prevention of product failures in production or use processes. They ascribe any performance within specification limits (between Upper Specification Limit (USL) and Lower Specification Limit (LSL)) as having no loss, whereas a performance outside the specification limits is ascribed a maximum loss, which is illustrated by the red line in the figure. However, even a small variation of geometric properties could lead to a deviation of product performance from its intended value, e.g. the necessary operating force, size of split lines between parts, lifetime, etc. – all of which can be perceived as a loss of quality to the user, but not necessarily a failure, illustrated by the black line in the figure. In general, every variation Δ_0 of a quality characteristic y around the originally planned target value m could lead to a reduction of functionality or quality and in the worst case will damage the company's reputation. Consequently, the occurring variation as well as the resulting monetary loss A_0 should be reduced by means of robust design solutions (Taguchi et al. 2005).

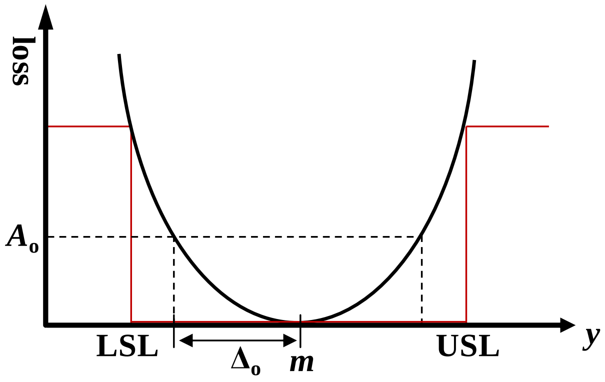

Figure 1. Quality loss function (Taguchi et al. 2005)

By means of Taguchi's Quality Loss Function, Robust Design is delimited from other research fields using the delimitation model in Figure 2. Horizontally, the basic difference between approaches focusing on variation and approaches aiming at the improvement of reliability, i.e. at a prevention of product failures, is shown. Vertically, the field of application is differentiated. Approaches for the control or the improvement of existing production processes are distinguished from approaches used in product development.

In the following, the paper concentrates on approaches applied in different phases of product development. The prevention of failures in production processes, e.g. by means of quality testing, check sheets, data based histograms and pareto diagrams (Ishikawa 1982) or Lean Manufacturing techniques such as visualization of occurring deviations and continuous improvement (Pojasek 2003), are not taken into account. The same applies to SPC approaches (MacCarthy, Wasusri 2002) for the control of production variation. Within product development, the main focus of the paper is on Robust Design approaches, as indicated in Figure 2. But as even literature on Robust Design usually also refers to corresponding methods from the field of Reliability Analysis (Hasenkamp et al. 2009), differences as well as the overlaps between Robustness and Reliability need to be further clarified.

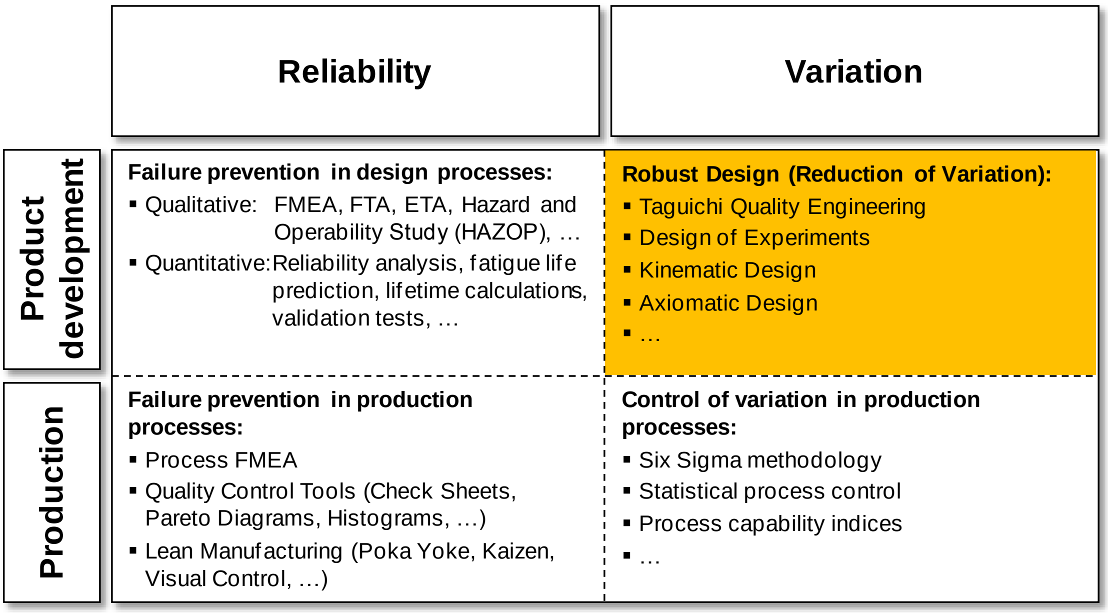

Figure 2. Delimitation of terms and corresponding methods

4 ROBUST DESIGN METHODS

4.1 Classification of RDM – state of the art

Previous literature reviews on RDM have to some extent provided an evaluation and classification of Robust Design Methods. Hasenkamp et al. (2009) distinguish between robust design principles, practices and tools. Based on the distribution of the reviewed contributions, it is concluded that there is a lack of 'practices' that describe what needs to be done. A wide array of contributions are grouped depending on their subject focus, e.g. the quadratic loss function, noise factors, experimental designs, but the details regarding how each subject is treated are not analyzed. Other authors evaluate the advantages and disadvantages of selected RDM's; for example, Lough et al. (2009) evaluate risk assessment techniques and Matthiassen (1997) gives a systematic description and evaluation of the dominant methods within robust design, and reaches the conclusion that there is a lack of early-stage methods.

For the classification, principles, methods and metrics are described. But seeing that the classification categories are leading/lagging, quantitative/qualitative, applicability in early/middle/late stages, it is only meaningful to classify the metrics and methods. Robust Design principles that describe ideas of how a design should be, but do not provide methods or metrics would not be possible to classify by any of the selected categories.

4.2 Robustness vs. Reliability

Robust design in its pure form focuses on the reduction of variation in functional performance. However, in literature, RDM are connected to a variety of methods and fields with objectives that differ in a number of ways. The most common connection seen is the one between robustness and reliability (Jugulum, Frey 2007). Prior to a classification of the individual robust design methods, the differences between robustness and reliability are clarified based on the delimitation model in Figure 2. Whereas a robust product ideally reacts insensitive towards all occurring variations within the processes of the product life cycle, the definition of reliability states (Bertsche 2008):

> *Reliability is the probability that a product does not fail under given functional und environmental conditions during a defined period of time.*

Consequently, Reliability approaches focus on the prevention of defective parts in production or the prevention of product failures when the product is shipped. Thereby, the product is usually interpreted as a parallel or serial structure of components. Based on a description of occurring failure modes and based on available information of failure rates, the overall failure probability of the system is calculated (Bertsche 2008). Risk Management techniques extend the analysis further to a consideration of resulting consequences for the user and the environment (Lough et al. 2009, Kumamoto 2007). Table 1 presents an overview of Reliability approaches. It contains commonly used methods such as the FMEA, the FTA, lifetime calculations for machine elements or product qualification tests (Bertsche 2008; Kumamoto 2007). For a comprehensive overview, these approaches are complemented by methods specifically conceived for the application in early design phases. Examples are statistically based lifetime calculations (Gandy et al 2006) or the assessment of product reliability based on a functional model within the Function Failure Design Method (FFDM) (Lough et al. 2009). Each method has been classified with respect to the success criteria from Section 2.3. The classification is done based on the authors' review and knowledge of RDM literature.

4.3 Classification of RDMs

In Table 2, Robust Design Methods focusing on the reduction of variation in functional performance have been classified in the same way that the methods focusing on product failure were classified in Table 1. The included methods have been selected in a semi-structured manner, by including the methods typically mentioned in robust design literature as well as methods mentioned in robust design literature reviews and surveys.

In the table, robust design frameworks such as Variation Risk Management (Thornton 2004) and Design for Six Sigma (Creveling et al. 2002) have not been included, because they are seen as management frameworks with underlying methods, which either are already included in the classification tables or are out of scope (as defined in Figure 2). Robust Design Principles, described by e.g. Matthiassen (1997) and Andersson (1996), are not methods, but are still included in the table.

By nature, they are leading and applicable in early stage, but they cannot be quantified. For example, a principle such as ‘design for self-reinforcement’ serves as a guideline, but not an indicator or metric.

Table 1. Methods to control failure probability

Method		Tool	Leading / lagging	Quantifiable metric	Quantitative / qualitative	Necessary information (Early/late application)
FMEA **(Bertsche 2008)**	Systematic procedure for the preventive assessment of possible failure modes	Form sheets	**Leading**	RPN	qual.	**Early** Expert experience
ETA (qualitative) **(Kumamoto 2007)**	Diagram to examine subsequent failure modes	/	**Leading**	/	qual.	**Early** Expert experience
FTA (qualitative) **(Bertsche 2008; Kumamoto 2007)**	Diagram to examine subsequent failure causes	/	**Leading**	/	qual.	**Early** Expert experience
HAZOP **(Kumamoto 2007)**	Examination of risk based on standardized guide words	Functional model / Lists of guide words	**Leading**	/	qual.	**Early** Expert experience
ETA (quantitative) **(Kumamoto 2007)**	Calculation of failure probability based on boolean logic	/	**Leading**	Probability of product failure	quan.	**Middle** - product architecture - subcomponent performance
FTA (quantitative) **(Bertsche 2008; Kumamoto 2007)**	Calculation of failure probability based on boolean logic	/	**Leading**	Probability of product failure	quan.	**Middle** - product architecture - subcomponent performance
FFDM **(Lough et al. 2009)**	Evaluation of the dependency of function failures	Functional model	**Leading**	Probability of function failure	quan.	**Middle** - bill of materials - historical data on function failure
Structural Integrity **(Geere, Goodno 2008)**	Calculation of stresses and strains in product components	Simulation software, hand calculations	**Leading**	Safety factor wrt. failure criterion	quan.	**Middle** - Material data - Load data - Component geometry
Probabilistic Risk Assessment (PRA) **(Kumamoto 2007)**	Evaluation of accidents for existing systems (usually complex plants, etc.)	Methodology	**Lagging**	Risk profiles	qual.	**Middle** - Product - Possible failures and accidents
Lifetime calculations **(Bertsche 2008)**	Lifetime prediction for mechanical elements based on empirical models	Damage accumulation hypothesis	**Leading**	Lifetime prediction	quan.	**Middle** - load spectrum - tolerable material load (Wöhler)
Variation based lifetime calculations **(Gandy et al. 2008)**	Stochastic lifetime prediction for mechanical elements	Damage accumulation hypothesis	**Leading**	Probability of lifetime	quan.	**Middle** - load spectrum - tolerable material load (Wöhler) - property variation
Qualification Tests **(Bertsche 2008)**	Empirical verification of lifetime based on different load testing conditions	Test system	**Lagging**	Lifetime prediction	quan.	**Late** - Prototype - detailed knowledge about failure mechanisms and existing load

Table 2. Methods to control variation in functional performance

Method		Tool	Leading / lagging	Quantifiable metric	Quantitative / qualitative	Necessary information (Early/late application)
Taguchi Methods **(Taguchi et al. 2005)**	Optimising parameter values and tolerances wrt. the sensitivity of each design parameter to obtain low variation in functional performance	N/A	**Lagging**	N/A	quan.	**Late** - Parameter values - Process capabilities
Design of Experiments **(Taguchi et al. 2005)**	Structured tests and simulations to optimise parameter values wrt. The signal-to-noise ratio	DOE procedure	**Lagging**	S/N-ratio (Signa-to-noise)	quan.	**Late** - Parameter values - prototypes or simulations
Axiomatic Design Information and Independence Axioms **(Suh 2001)**	1) Identification of design parameters controlling more than one functional requirement 2) Identification and reduction of the information contributing to a functional requirement	Coupling Matrix and No. of design parameters	**Leading**	N/A	qual.	**Middle** - Design parameters - functional requirements
Kinematic Design, Design Clarity, Minimum Constraint Design **(Ebro et al. 2012; Söderberg, Lindkvist 2002)**	Quantifying the clarity and quality of design constraints as well as the mobility of the design	Kutzbach Equation and Robustness Cockpit	**Leading**	Mobility	quan.	**Early** Product Architecture
Locating Schemes **(Söderberg et al. 2006)**	A quantification of the transfer function, converting the gradient into a metric	RD&T Software, Locating schemes	**Leading**	Instability & Quality Appearance Indices	quan.	**Middle** - Design parameters - functional requirements
Robust Design Principles **(Matthiassen 1997; Andersson 1996)**	Collection of good design principles, that lead to robust design.	N/A	**Leading**	N/A	N/A	**Early/Middle** (Depending on the individual principle)

5 ANALYSIS OF RESULTS

Ultimately, the objective of robust design research is the application of suitable RDM in industrial practice. Based on the identified success criteria for an industrial application, the elaborated classification needs to be visualized to give a structured overview of available approaches. Based on the visualization, findings and necessary extension to available RDM are discussed.

5.1 Classification Model RDMs – Visualization

A visual representation of the classification in Tables 1&2 is shown in Figure 3. First of all, two of three success criteria for the industrial application of RDM are used to define the basic framework of the representation. Vertically, leading and lagging methods are distinguished. Horizontally, the methods are placed according to when in the development process they can be applied (early, middle, late). Finally, the third criterion is visualized by means of round or rectangular shapes, i.e. the distinction between qualitative approaches relying on subjective expert assessments and quantitative, objective methods. In this way, the classified methods from the fields a) Reliability Analysis and b) Robust Design can be assigned according to their applicability and their value within design.

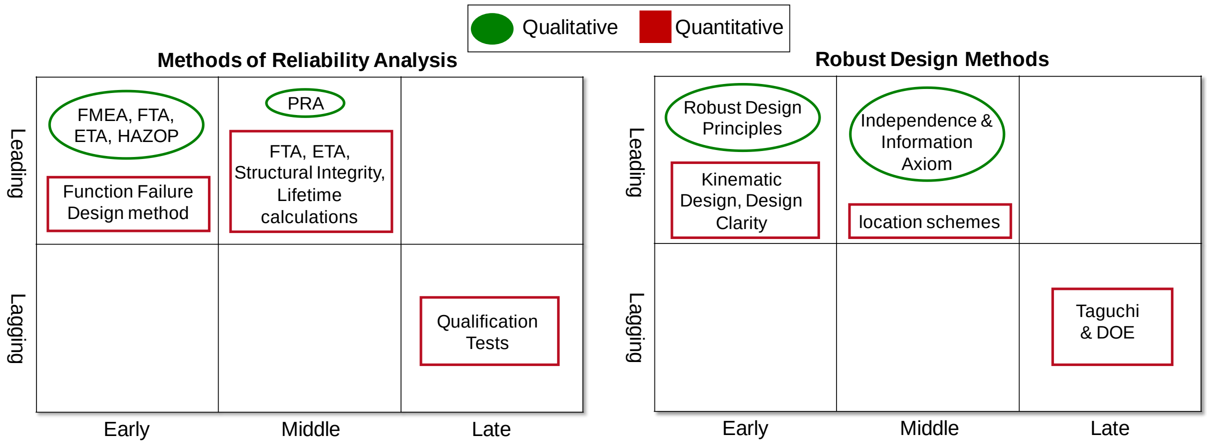

Figure 3. Visualization of classifications

5.2 Discussion

The visualization of the classification in Figure 3 illustrates the current body of available approaches for an analysis and improvement of Reliability as well as of existing RDM. The mapping of the methods gives the designer a structured overview of the available RDMs and assists in selecting a method, which fits with the type of analysis and result that is wanted. On this basis a number of observations can be made:

- First of all, the designer can distinguish between methods refering exclusively to reliability, i.e. failure probability or predicted lifetime, and methods focusing on the reduction of variation. On the whole, there are no distinct ‘white-spots’ on the map, where no methods are available. However, it is the impression of the authors that RDM-literature focuses on FMEA, DOE and Taguchi methods, none of which fulfill the industrial criteria derived on section 2.3.
- Especially, existing quantitative approaches for an assessment of reliability largely depend on available information pertaining past product failures, i.e. empirically described failure criteria, databases with existing failures or tests. This leads to the tendency that reliability is usually calculated for well known products or large systems as well as in late design phases, when reliability data of different subcomponents is available. Examples are machine elements (Bertsche 2008), power plants, and train transport (Kumamoto 2007). Even approaches that explicitly refer to the necessity of an early, quantitative assessment rely on historical data. Whereas the consideration of possible variation in lifetime calculations is based on available damage accumulation hypotheses, the FFDM uses archived information of existing products.
- The same problem applies to qualitative approaches classified as leading. Qualitative methods in the field of reliability as well as Robust Design are based on subjective expert assessments. Thus, the obtained results also largely depend on detailed experiences and subjective estimations of the designer in charge. Used indicators, e.g. the Risk Priority Number within the FMEA, could somewhat also be classified as lagging.
- A main shortcoming of the current body of available methods is that no objective and quantifiable indicators exist for an early and easy to apply evaluation of the systems robustness in highly iterative development projects. The right hand side of Figure 3 shows that the current approaches, also applied in industry even just to a limited extent as discussed in section 2.1, focus on late design stages. Approaches, such as DOE and Taguchi’s Quality Engineering, are based on experimental analyses of existing prototypes and consequently are lagging indicators which only are applicable in the middle or late stages. This makes it challenging for a designer to make data-driven decisions in early design stages.

Consequently, a shift in focus to methods such as kinematic design and design clarity (Ebro et al. 2012) that provide an easy to calculate, objective and quantifiable robustness metric could be valuable for the field. In general, the conversion of existing Robust Design principles that describe the basic idea how a design should be (Matthiassen 1997; Andersson 1996) into operational methods with corresponding metrics could be a subject for further research.

Another important conclusion for further research, drawn from the classification, is the lack of methods to analyse the impact of noise factors. For the choice of suitable RDMs, the existing dependencies between occuring disturbances and the products performance need to be described by a suitable transfer function as early as possible. Available approaches, e.g. Taguchi's Quality Engineering, strongly rely on DOE, thus cannot be applied until a first prototype exist. In general, the establishment of transfer functions in different design stages is usually not explained in a detailed manner (Hasenkamp et al. 2009; Jugulum, Frey 2005). Even qualitative approaches are either exclusively based on expert assessments, e.g. the Variation Mode and Effects Analysis (Johansson 2006), or refer to specific applications, e.g. the analysis of a dish washing machine (Pons, Raine 2005). To analyze the wide variety of influencing factors in the product life cycle (Eifler et al. 2012), a comprehensive approach for a systematic assessment of existing noise factors and the analysis of existing dependencies in life cycle processes is elaborated within the Uncertainty Mode and Effect Analysis (UMEA) (Engelhardt et al. 2011).

6 CONCLUSION

The use of Robust Design Methods in industry is limited. Based on statements from industrial surveys and the authors' experience from working with industrial design in industry, it is suggested that the barriers for industrial implementation of RDM is the lack of early-stage methods that can provide the design team with leading and quantifiable metrics in a simple and fast manner. Using this assumption, success criteria for the implementation of RDM in industry and a classification of the current body of robust design methods are presented.

The presented classifications show that actually only a limited number of methods focus on the reduction on sensitivity to variation, i.e. product robustness. Instead, commonly used methods either focus on the prediction and prevention of failures, i.e. reliability, or on the control of production variation. Furthermore, the surveys' statements are confirmed. Especially in early design stages, only a limited number of leading and quantitative methods is available. Existing methods most often rely on data from previous projects and the experience of the design team or require extensive information on failure criteria, parameter values, tolerances, etc. Consequently, they cannot be applied until later design stages which makes design changes significantly more costly.

It is concluded, that the low use of RDM in industrial practice can be explained by the lack of operational tools to fulfill the existing Robust Design principles. Without the benefit of a quantifiable metric it is usually unclear to which extent a principle has been followed. Consequently, a suitable framework with leading, early-stage, and quantitative methods and metrics must be developed. Moreover, the concept of the transfer function must be converted from a principal and theoretical representation to an operational tool. These extensions of the current body of RDM needs to be embedded in a coherent Robust Design process that takes into account the dependencies between different design models and can gradually be detailed in every design stage.

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REFERENCES

Andersson, P. (1996) *A Process Approach to Robust Design in Early Engineering Design Phases*. Sweden, Lund Institute of Technology.

Araujo, C.S., Benedetto-Neto, H., Campello, A.C., Segre, F.M. and Wright, I.C. (1996) The utilization of product development methods: A survey of UK industry. *Journal of Engineering Design,* Vol. 7, No.3, pp. 265-277.

Araujo, C.S. (2001) *Acquisition of Product Development Tools in Industry: A Theoretical Contribution*. Denmark, Technical University of Denmark.

Bertsche, B. (2008) *Reliability in Automotive and Mechanical Engineering*. Berlin, Heidelberg, Springer.

Creveling, C.M., Slutsky, J. and Antis, D. (2002) *Design for Six Sigma in Technology and Product Development*. United States, Prentice Hall.

Ebro, M., Howard, T.J. and Rasmussen, J.J. (2012) The Foundation for Robust Design – Enabling Robustness through Kinematic Design and Design Clarity. *Proceedings of the International Design Conference – DESIGN '12,* Croatia, pp. 817-826.
Eifler, T., Enss, G.C., Haydn, M., Mosch, L., Platz, R. and Hanselka, H. (2012) Approach for a consistent description of uncertainty in process chains of load carrying mechanical systems. *Applied Mechanics and Materials,* Vol. 104, pp. 133-144.
Engelhardt, R., Wiebel, M., Eifler, T., Kloberdanz, H., Birkhofer, H. and Bohn. A. UMEA – A follow up to analyze uncertainties in technical systems. *Proceedings of the 18th International Design Conference – ICED '11*, Denmark, pp. 257-266.
Gandy, A., Jäger, P., Bertsche, B. and Jensen, U. (2006) Berücksichtigung von Ungenauigkeiten bei Zuverlässigkeitsanalysen in frühen Entwicklungsphasen. *Konstruktion*, No. 6, pp.78-82.
Geere, J.M., Goodno, B.J. (2008) *Mechanics of Materials*. Toronto, Cengage Learning.
Lough, K.G., Stone, R. and Tumer, I.Y. (2009): The Risk in Early Design Method. *Journal of Engineering Design*, Vol. 20, No. 2, pp. 155-173.
Gremyr, I., Arvidsson, M. and Johansson, P. (2003) Robust Design Methodology: Status in the Swedish Manufacturing Industry. *Quality and Reliability Engineering International*, Vol. 19, pp. 285-293.
Hasenkamp, T., Arvidsson, M. and Gremyr I. (2009) A Review of Practices for Robust Design Methodology. *Journal of Engineering Design*, Vol. 20, No. 6, pp. 645-657.
Ishikawa, K. (1982) *Guide to Quality Control*. Tokyo, Asian Productivity Organization.
Johansson, P., Chakhunashvili, A., Barone, S. and Bergman, B. (2006) Variation Mode and Effect Analysis: a Practical Tool for Quality Improvement. *Quality and Reliability Engineering International*, Vol. 22, pp. 865-876.
Jugulum, R. and Frey, D.D. (2007) Towards a Taxonomy of Concept Designs for Improved Robustness. *Journal of Engineering Design*, Vol. 18, No. 2, pp. 139-156.
Kumamoto, H. (2007) *Satisfying Safety Goals by Probabilistic Risk Assessment*. London, Springer.
MacCarthy, B.L. and Wasusri, T. (2002): A Review of Non-standard Applications of Statistical Process Control (SPC) charts. *International Journal of Quality & Reliability Management*, Vol. 19, No. 3, pp. 295-320.
Matthiassen, B. (1997) *Design for Robustness and Reliability – Improving the Quality Consciousness in Engineering Design*. Denmark, Technical University of Denmark.
Pojasek, R.B. (2003) Lean, Six Sigma, and the Systems Approach: Management Initiatives for Process Improvement. *Environmental Quality Management*, Vol. 13, No. 2, pp. 85-92.
Pons, D.J. and Raine, J.K. Simulation of key performance characteristics under uncertainty. *Journal of Engineering Manufacture*, pp. 151-162.
Suh, N.P. (2001) *Axiomatic Design: Advances and Applications*. United States, OUP.
Söderberg, R. and Lindkvist, L. (2002) Stability and seam variation analysis for automotive body design. *Journal of Engineering Design*, Vol. 13, No. 2, pp. 173-187.
Söderberg, R., Lindkvist, L. and Carlson, J.S. (2006) Managing physical dependencies through location system design. *Journal of Engineering Design*, Vol. 17, No. 4, pp. 325-346.
Taguchi, G., Chowdhury, S. and Wu, Y. (2005) *Taguchi's Quality Engineering Handbook*. New Jersey, John Wiley & Sons Inc.
Thornton, A.C., Donnelly, S., Ertan, B. (2000) More than just Robust Design: Why product development organizations still contend with variation and its impact on quality. *Research in Engineering Design*, Vol. 12, pp. 127-143.
Thornton, A.C. (2004) *Variation Risk Management: Focusing Quality Improvements in Product Development and Production*. New Jersey, John Wiley & Sons Inc.