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DESIGN FOR ROBUSTNESS - SYSTEMATIC APPLICATION OF DESIGN GUIDELINES TO CONTROL UNCERTAINTY

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Abstract

In Robust Design literature, the application of Robust Design guidelines is suggested as a measure to obtain a design that is more insensitive against variations. But it lacks a detailed and systematic overview of already existing design advice that can be transferred to robust design tasks. The authors provide a literature investigation of design advice in engineering design literature, derive criteria to assess its applicability for robust design tasks based on transfer functions and noise behaviour models. The research shows that almost half of the existing design advice is also suitable for robust design. To include the design advice catalogues into the development process, the authors suggest a procedure that is allocated within the integrated product and process development process. It consists of opportunistic analysis and synthesis steps and should be applied up from working principle level. To quantify the potential of robust design advice application, the robustness potential indicator is introduced. It represents the degree of robust design advice consideration.

Keywords: Robust design, Knowledge-Based Engineering (KBE), Uncertainty, Design for X (DfX)

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1 INTRODUCTION

Taguchi, the godfather of Robust Design (RD), once claimed that a design can only be made more robust in late design phases through design optimisation in parameter design. Nowadays however, it is widely accepted, that there are measures that can be also applied earlier in the design process (Andersson, 1996). One measure that can be useful in early phases is the application of experience based design advice that increases the robustness of a design. In literature, some publications can already be found that provide some RD specific advice (Ebro et al., 2016; Matthiassen, 1997), but there is still a lack of systematic research aggregation that shows the potential of the huge variety of existing design advice for RD tasks. This is the objective of this paper. In detail, the research questions behind this publication are: Considering the huge amount of experience based design advice in egineering, can more suitable design advice be found that can be applied in robust design? If yes, how can this advice be characterised? How can it, in the next step, be organised to provide support for designers aiming for robustness, considering the usual compromises during design concretisation?

2 SCIENTIFIC APPROACH AND ARGUMENTATION

Figure 1 illustrates the scientific approach. In section 3, the starting point of the literature research contains literature that contributes somehow to the field of robust design in the context of the *collaborative research centre SFB 805* and the *Robust Design SIG* of the *design society*. Considering all the robustness-related literature sources of these documents and the literature sources of the sources and so on leads to a detailed literature network where main titles can be easily identified through the number of citations. The authors assume that all relevant basic documents, at least in the European RD context and the US, have been found that way (the whole data gathered is object to further publications). The robust design literature is then used to find the existing ways in which a product's robustness can be increased. These characteristics serve as classification criteria when assessing design advice from design science literature.

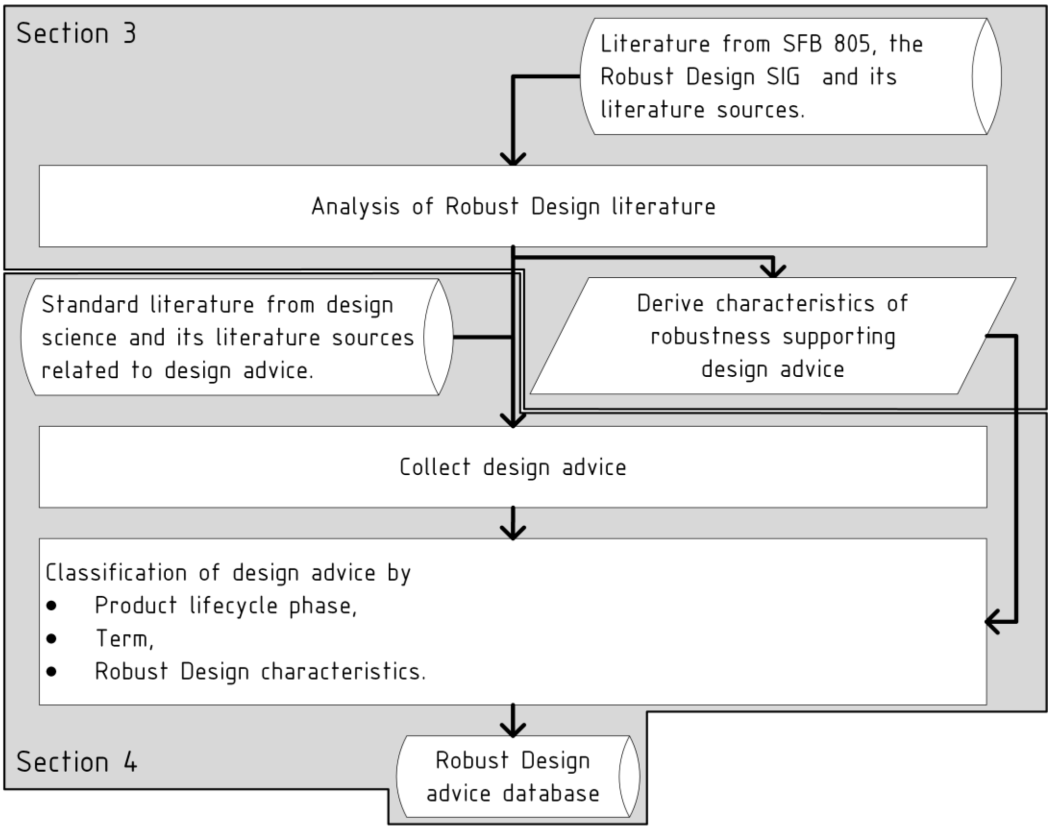


Figure 1: Scientific procedure in order to derive the Robust Design advice database.

In section 4, the authors present literature from the RD and basic Design Science literature that contribute to the topic of design advice. Tracing the literature sources and the sources of the sources and so on, all kinds of design advice that can be identified in over 150 documents are stored in an Excel file, the RD advice database. In order to derive the main titles of the literature network, the titles are scaled in size according to their number of citations within the network. The authors assume that the majority of design advice related to basic rules, design principles and design guidelines has been identified for the lifecycle phases production and use. The literature research generally results in such a large amount of information being extracted, that it was decided to concentrate on these two main lifecycle phases.
Applying the Characteristics of RD measures found in section 3 to the database, robustness supporting design advice can be identified. The results are presented at the end of section 4.

3 CHARACTERISTICS OF ROBUSTNESS-SUPPORTING DESIGN ADVICE

To identify the suitability of the design advice for RD, several criteria are needed. To get an overview on how robustness is seen in literature, titles in the context of the *SFB 805* and the *Robust Design SIG* and their sources were analysed. Titles used as a starting point include Eifler (2014), Suh (1990), Ebro (2015), Engelhardt (2012), Söderberg et al. (2006), Mathias (2015), Matthiassen (1997), Arvidsson and Gremyr (2008), Andersson (1996).
Ulrich and Eppinger (2008) is often used as a definition of robustness. They define a robust product or process as "one that performs as intended even under nonideal conditions such as manufacturing process variations or a range of operating situations". Based on this definition two criteria can be derived:

1. Decrease in performance variation
2. Handling of noise

During this work, it became apparent, that these criteria are too abstract for determining the suitability for Robust Design. To find more specific characteristics, the literature was further investigated. Several detailed approaches were identified. To cluster them two well established models from the RD context were chosen: the Transfer Function (Ulrich and Eppinger (2008)) and the Noise-Product-Behaviour-Model. All identified characteristics are listed in Table 1.

Table 1: List of characteristics with examples

Model	#	Characteristic	Example
Transfer Function	1	Exploiting flat sections of the function by shifting of the working point	Optimise parameters
	2	Reducing/ eliminating variation in positioning	Use self-positioning; provide stop dogs
		Increasing product quality/ decrease in variation of product characteristics	With cast components, avoid vertical sections
	3	Exploiting elasticity	Apply principle of elasticity
		Achieving independence of functions	Decouple functions
		Increasing predictability	Seek exactly constrained systems
	4	Increasing range of tolerance for performance variation	Change requirements
		Facilitating quality control	Use measurable dimensions
	Other	Standardising of products and processes	Reuse models; use standard parts
		Reducing potential for occurrence of failures	Simplify the geometry; Reduce number of parts
Noise-Behaviour Model	1	Reducing/ eliminating noise	Isolate heat source
	2	Reducing/ eliminating influence of noise	Isolate component/product
	3	Reducing/ eliminating impact of noise	Use symmetric structure; apply principle of self-help
		Increasing future robustness	Increase modularisation

The Transfer Function shows the relation between variation in design parameters and functional performance. The identified characteristics listed in Table 1 can be assigned to four RD measures within the Transfer Function, which all reduce functional performance variation. For an illustration of the measures see Figure 2. A similar approach is used by Ebro and Howard (2016).

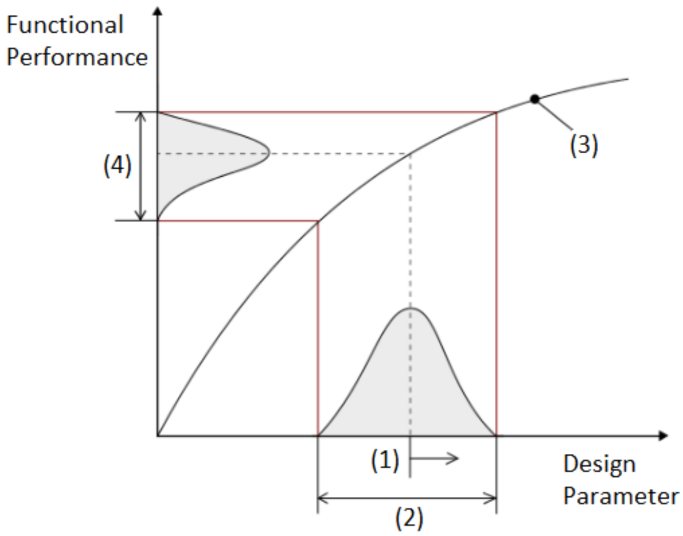


Figure 2: Illustration of the Transfer Function with four strategies

The Noise-Product-Behaviour-Model grades the influence of noise on the product behaviour. It is based on a model which connects disturbances and product function created by Mathias et al. (2010) and is displayed in Figure 3. To reduce variation in the product behaviour, three measures are identified. They reduce or eliminate the influence or impact of noise or the noise itself. Whether the influence, impact or the noise itself is reduced or eliminated depends on the design advice and its implementation. The concrete characteristics are listed in Table 1 as well.

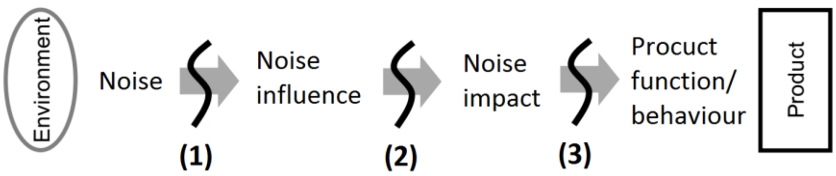


Figure 3: Model of connection between noise and product behaviour with three measures, according to Mathias et al. 2010

4 DESIGN ADVICE ANALYSIS

In literature, a multitude of different design advice exists. There is advice for different fields of engineering design such as manufacturing processes, EcoDesign or product modularisation and for different stages of the design process. Furthermore, a variety of expressions are used. Among them are: guideline, principle, rules, heuristic, axiom or maxim. Additionally, those expressions are defined differently by different authors. To provide an overview, literature is searched systematically and a network on main authors in the field of design guidelines is derived. At the end of the section, the result of the literature review, the design for robustness database, is introduced and evaluated.

4.1 Design Advice in Literature

As a starting point for the search, titles in engineering design and Robust Design were chosen. The titles include the list given at the beginning of section 3 along with Feldhusen et al (2007) and French (1994). They were examined for design guidelines and referenced titles or authors that mention design guidelines. The cited titles were then further researched and so on. For the search, the table of contents and the abstract or the introduction were scanned for keywords such as principle, rules, guidelines, heuristics, axiom and their German respectives. Promising chapters were then looked into further. If design advice was found, it was collected in an Excel list as presented in section 4.3. The references between titles were recorded as well.

As there are innumerable guidelines for different processes in manufacturing and assembly, the search field needed to be narrowed down. Guidelines for manufacturing and assembly were taken from main authors in engineering design while the original literature was not further analysed. The main authors had already preselected design guidelines and are widely accepted in the design field.

4.2 Network of main authors

The references between titles were listed and plotted. The emerging network gives information about main authors in the field of design advice. It is displayed in Figure 4. The bigger the font size, the more often this title or author is mentioned. Some authors, as is the case with French, Suh and Roth, have several publications on design advice. For a better comparison, the citations of these works were combined as well as the references to English and German editions of the same title.
During the literature review, 150 publications were revised. 96 of them were referenced at least once. Only five publications were referenced more than five times. With 31 citations, Feldhusen et al. (2007) is identified as the main work. It includes a great collection of design advice, divided into three sections: basic rules, design principles and design guidelines. This subdivision is also used in this research as a categorisation (see section 4.3). Second most cited author is French with 18 citations. He published a list of design principles (French 1994). Other publications on design advice are French (1992a, 1992b, 1993, 1999). Suh, known for the method of axiomatic design, is cited eleven times. The Publications include Suh (1990, 2001). Roth (2000, 2001) is mentioned nine times. Six authors refer to Matthiassen (1997). He collected principles for robustness and reliability.

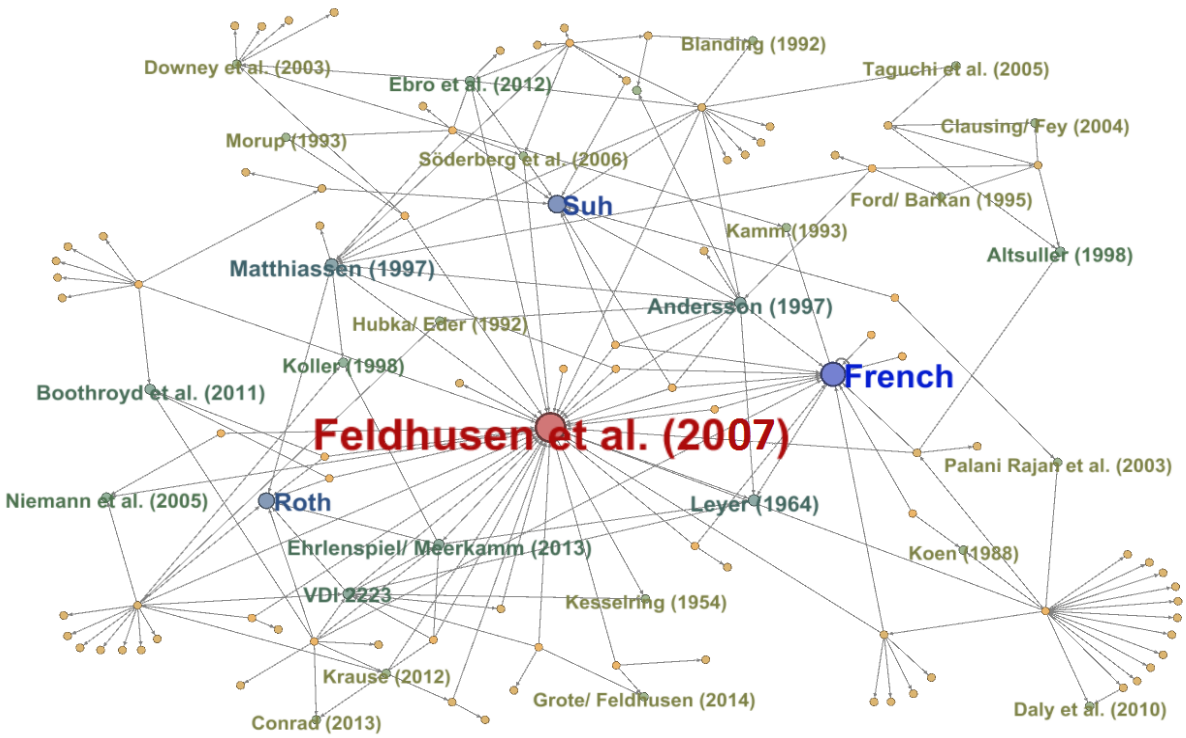


Figure 4: Network of Literature to find main authors in the field of design guidelines

4.3 Design for Robustness (DfR) Database

The design advice was collected in an Excel list. Figure 5 shows an extract of said list. It consists of four main parts:

1. Title of the design advice and main authors are given. The advice is clustered by topics.
2. Ranking of suitability for Robust Design: possible entries are *(+) positive impact, (~) partial, impact, (−) no impact* and *(↯) negative impact* on robustness upon using the design advice.
3. Classification by term: possible categories are *basic rule, design principle* and *design guideline*.
4. Classification by life phase: possible categories are *development, manufacturing, assembly, use, maintenance* and *recycling*.

Each piece of advice was individually rated by the authors for its potential to increase the robustness of a product or process. For this purpose, the characteristics presented in section 3 were used. For example, the guideline 'reduce stiffness' (see Figure 5) fits the characteristic 'exploiting elasticity' (see Table 1). Therefore, it has a positive impact on robustness. Subsequently, the advice was also classified by term and life phase, in which the robustness is increased. The terms and their definitions are adopted from the works of Feldhusen et al. (2007). The classification by life phase is linked to the working hypothesis of the SFB 805, which locates the origin of uncertainty within processes (Hanselka and Platz, 2010). The classifications by term and life phase can be used to filter the database to use the design advice in the product development process.

	I		II	III			IV					
	Design Advice	**Author**	**RD suitability**	**basic rule**	**design principle**	**design guideline**	**development**	**manufacturing**	**assembly**	**use**	**maintenance**	**recycling**
clarity	clarity	Feldhusen et al. (2013), p. 492; French (1994), p. 229; French (1992), p. 210;	+	x			x	x	x	x	x	x
	aim for clarity of function	French (1999), p. 212	+		x		x					
elasticity	principle of elasticity	French (1992), p.209; Ebro/ Howard (2016), p.91–92	+		x				x	x		
	reduce stiffness	Suh (2001), p.45–46	+			x			x	x		

Figure 5: Extract from the list of design advice

4.4 Discussing the results

An evaluation of the list by suitability for Robust Design is given in Figure 6. From a total 999 pieces of design advice, 50% are supporting robustness. However, it should be kept in mind, that the literature was preselected.

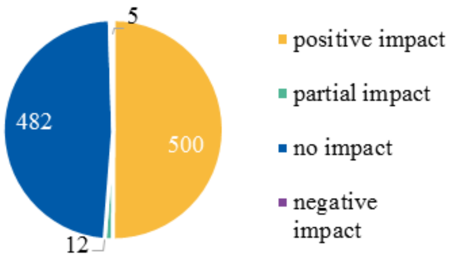


Figure 6: Evaluation of the list of design advice by suitability for Robust Design

The evaluation by term and life phase is shown in Figure 7. The entire list of design advice found during the literature research is compared to the advice identified as suitable for Robust Design. Design advice characterised as suitable has a positive or partially positive impact on robustness. A consistent rate of 40% to 60% of robustness-supporting advice is found in these charts, except for the category of basic rules and the phase of recycling. The high percentage of basic rules is due to the abstract character of this type of design advice, as many aspects of design are included in basic rules. The low percentage in recycling is explained by the lack of relevance to robustness of this phase.

The number of design advice identified increases parallel to the degree of specificity with the highest number in the category of design guidelines (see Figure 7a). The evaluation by life phase shows, that the phases of manufacturing, assembly and use are supported best (see Figure 7b).

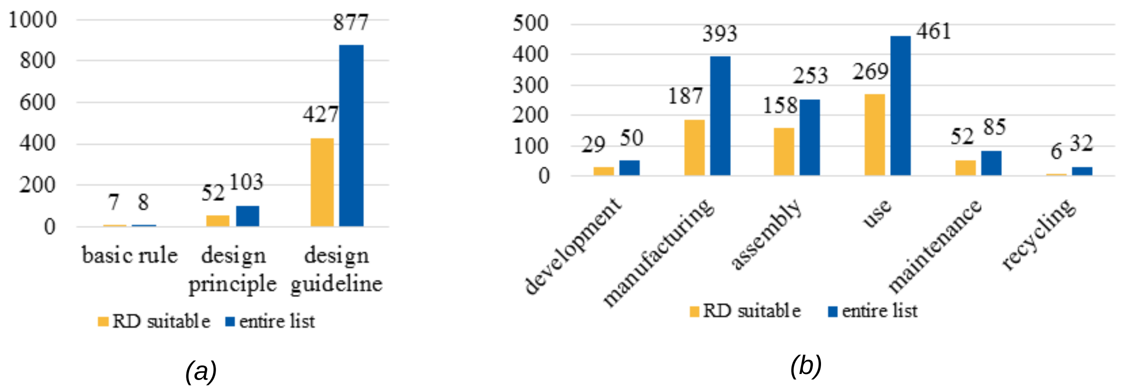


Figure 7: Evaluation of the list of design advice by term and life phase

4.5 Editing the Design Advice

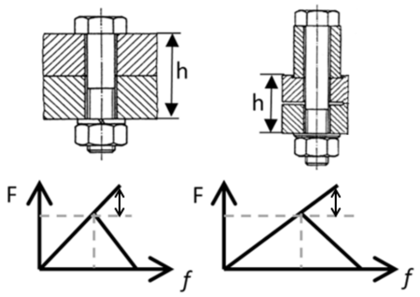
To enable the use of the database without additional literature, the data is further processed. To each piece of design advice an explanation is added, the potential for increase of robustness is pointed out and the advice is illustrated by an example of a technical application. An example is given in Figure 8. The index card with the edited design advice is used as the output upon filtering the database.

Principle of Minimizing Failures

Explanation The principle of Minimizing Failures aims for insensitive Transfer Functions. This way, variation in design parameters results in less variation in functional performance.

RD-Potential Reducing/ eliminating impact of noise

Example The example shows a common bolt connection (left) and a waisted bolt (right) with their respective Rötscher-Diagram. The extended force distance in the waisted bolt leads to a more even Transfer Function. This way, variation in elongation of the bolt has less effect on the value of the force.



Author Krause (2000), p.130, p.150; Suh (2001), p.54-46

Figure 8: Exemplary index card with design advice

5 CONSIDERING DESIGN GUIDELINES IN ROBUST DESIGN

The potential for applying design guidelines in engineering design processes is broadly accepted in academia and industry. However, it still lacks a consistent database to systematically find guidelines which have the potential to be applied in RD tasks. As shown in Section 2 and Section 3, there is a huge amount of already existing design guidelines that can be transferred to RD problems. To do so, an adequate method is needed. This is the subject of this section.

5.1 Design for Robustness (DfR) - Procedure Model

The Robust Design process is part of the general design process. This process, specifically the integrated product and process development (IPPD) according to Birkhofer (2012), illustrates the relations between the design phase and real processes, such as production and product use. While product development must anticipate the processes of the product life-cycle, decisions made during development also influence the product life-cycle. Robust Design must be implemented as early as possible in the development process to maximize its impact (Andersson, 1996). As the Robustness of a product is mainly influenced by the design parameters of the product, the earliest point to apply robustness increasing measures is the working principle level during conceptual design. This is where physical effects are implemented through working bodies and working surface pairs. Design for Robustness (DfR) is an additional process, that faces uncertainty in all product life phases as well as in the process development chain itself. It is the foundation of the efficient application of robustness optimisation and parameter design in later design phases.

The DfR process consists of opportunistic analysis and synthesis steps (Figure 9), both supported by design advice provided by the robust design advice database. For every part (subsystem) of the product potentially interesting guidelines for increasing the robustness of the product can be identified, using the product life-cycle as a filtering characteristic of the database. As shown above, the authors suggest a filtering characteristic that divides the main process steps of the product lifecycle into sub processes. *Production* is divided into *manufacturing* and *assembly*, *product use* into *use* and *maintenance*. This is done for a better differentiation of the processes.

Analysis Step:

1. **Choose Solution**
   Define the focus of the investigation.
2. **Choose Process**
   Decide which of the product life-cycle processes is of interest for the analysis.
3. **Get Design Advice**
   Access data stored in the Robust Design Guideline Database. All guidelines found are potential robustness supporting design guidelines. Analyse which Robust Design Advice is already considered in the solution and which is not.

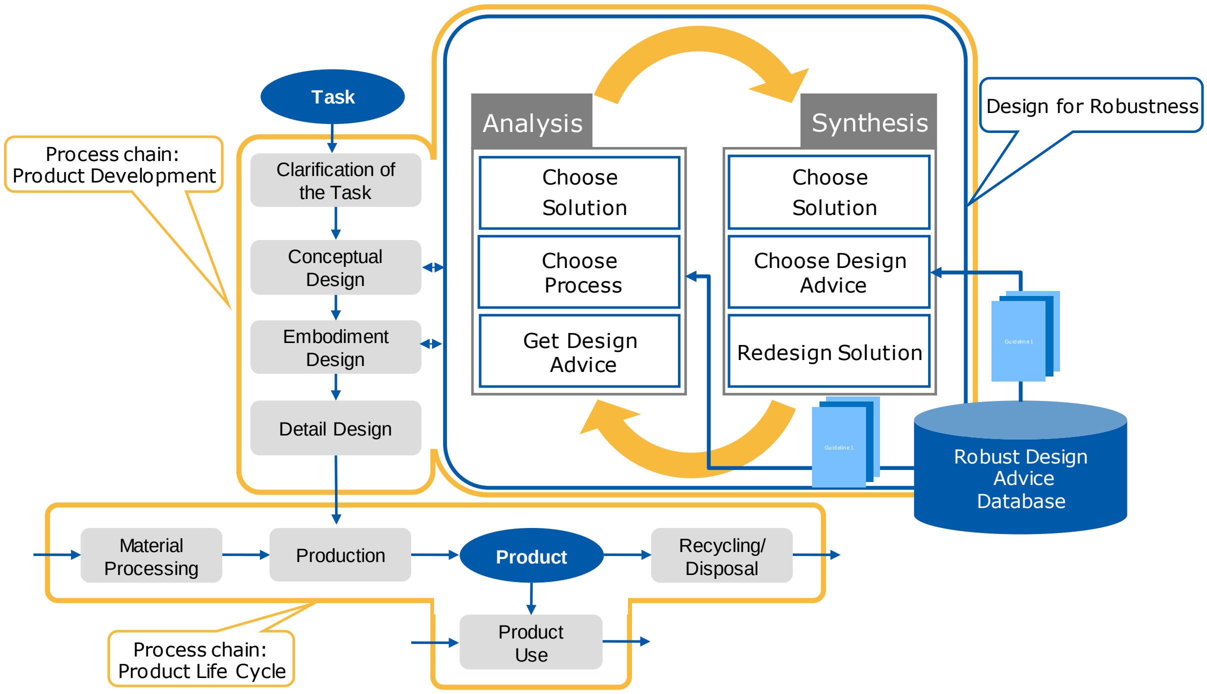


Figure 9: Design for Robustness procedure allocated in the integrated product and process development process (IPPE)

Synthesis Step:

1. **Choose Solution**
   Define focus of synthesis step.
2. **Choose Design Advice**
   Use the potential robustness supporting design advice found during the analysis step and choose one to be applied.
3. **Redesign Solution**
   Find new solution variants through the application of potential robustness supporting design advice. The more potential robustness supporting design guidelines are considered, the higher the probability is to obtain a robust solution.

6 CONCLUSION AND OUTLOOK

Based on the aforementioned research questions the authors gave an overview of the most relevant literature related to design guidelines and pointed out Pahl and Beitz's *Engineering Design* as the most cited title. The analysis is based on a literature research of 150 titles and leads to approximately 1000 design guidelines.

The authors provide a set of systematically derived characteristics to find the guidelines that can be used to increase a design's robustness based on broadly accepted models such as the *Transfer Function*. One of the main insights is the almost 50% ratio of applicability (Figure 6, Figure 7), that shows the potential for already existing design guidelines to also be applicable in Robust Design. The derived characteristics work well to structure a database for robust design tasks. Further structuring criteria are the type of advice (basic rule, principle and guideline) and the life phase related to the advice.

The Robust Design Advice Database can be used following the proposed procedure model presented in section 5.1, which is based on the integrated product and process development. The suggested opportunistic analysis and synthesis steps are a common and already implemented way to solve problems within development processes. Therefore, they are also found to be useful in RD tasks to provide a consistently structured development procedure.

The next step must show the applicability of the procedure and the database in industrial development projects. The experience must be transferred back into academia to ultimately provide a useful set of tools for RD tasks. Additionally, even more design advice has to be collected. Especially the potential for controlling uncertainty in human factors through design advice application. This has not been investigated yet and needs more attention.

REFERENCES

Andersson, P. (1996), *A process approach to robust design in early engineering design phases*. Diss., Lund.

Arvidsson, M. and Gremyr, I. (2008), “Principles of robust design methodology”, *Quality and Reliability Engineering International*, Vol. 24 No. 1, pp. 23–35.

Birkhofer, H.; Rath, K.; Zhao, S. (2012), “Umweltgerechtes Konsruieren”. In: Frank Rieg und Rolf Steinhilper (Hg.): *Handbuch Konstruktion*. München: Hanser, S. 561–581.

Ebro Christensen, M. (2015), *Applying Robust Design in an Industrial Context*, Diss., Technical University of Denmark, Lyngby, 2015.

Ebro, M.; Howard, T. J. (2016), “Robust design principles for reducing variation in functional performance”. In: *Journal of Engineering Design* 27 (1-3), 75–92, http://doi.org/10.1080/09544828.2015.1103844

Eifler, T. (2014), *Modellgestützte Methodik zur systematischen Analyse von Unsicherheit im Lebenslauf technischer Systeme*, Dissertation, Technische Universität Darmstadt, Darmstadt, 2014.

Engelhardt, R.A. (2012), *Uncertainty Mode an Effects Analysis - heuristische Methodik zur Analyse und Beurteilung von Unsicherheiten in technischen Systemen des Maschinenbaus*, Dissertation, Technische Universität Darmstadt, Darmstadt, 2012.

Feldhusen, J.; Grote, K.H.; Pahl, G.; Beitz, W.. (2007), *Engineering Design - A Systematic Aproach* // Engineering Design. A Systematic Approach. 3 // Third Edition. London: Springer-Verlag London Limited. http://doi.org/10.1007/978-1-84628-319-2.

French, M. J. (1992a), *Form, structure and mechanism*. Houndmills: MacMillan.

French, M. J. (1992b), “The opportunistic route and the role of design principles”. In: *Research in Engineering* Design 4 (3), S. 185–190. http://doi.org/10.1007/BF01607946

French, M. J. (1993), “The nature, use and teaching of design principles”. In: *International Journal of Mechanical Engineering Education* (21), S. 241–255.

French, M. J. (1994), “An annotated list of design principles”. In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (208), S. 229–234.

French, M. J. (1999), *Conceptual design for engineers*. 3. ed. London: Springer.

Hanselka, H.; Platz, R.. (2010), An“sätze und Maßnahmen zur Beherrschung von Unsicherheit in lasttragenden Systemen des Maschinenbaus”. In: *Konstruktion: Zeitschrift für Produktentwicklung und Ingenieur-Werkstoffe* (11/12), S.55-62.

Krause, W.; Bürger, E. (Hg.) (2000), “Gerätekonstruktion”. In *Feinwerktechnik und Elektronik*. 3., stark bearb. Aufl. München: Hanser.

Mathias, J.; Kloberdanz, H.; Engelhardt, R.; Birkhofer, H. (2010), “Strategies and Principles to Design Robust Products”. In: Dorian Marjanović (Hg.), Design 2010. *11th International Design Conference*, Dubrovnik - Croatia, May 17 - 20, 2010. Sveučilište u Zagrebu; Design Society; International Design Conference. Zagreb: Design Society, S. 341–350.

Mathias, J. (2015), *Auf dem Weg zu robusten Lösungen – Modelle und Methoden zur Beherrschung von Unsicherheit in den Frühen Phasen der Produktentwicklung*, Dissertation, Produktentwicklung und Maschinenelemente, Technischen Universität Darmstadt, Darmstadt, 2015.
Matthiassen, B. (1997), *Design for robustness and reliability. Improving the quality consciousness in engineering design*. Diss., Lyngby.
Roth, K. (2000), *Konstruieren mit Konstruktionskatalogen. Band 1: Konstruktionslehre. 3. Aufl., erw. und neu gestaltet*. Berlin: Springer (Konstruieren mit Konstruktionskatalogen, / Karlheinz Roth ; Bd. 1). http://doi.org/10.1007/978-3-662-08152-5
Roth, K. (2001), Kon*struieren mit Konstruktionskatalogen. Band 2: Kataloge. 3. Aufl., mit wesentlichen Erg*. Berlin: Springer (Konstruieren mit Konstruktionskatalogen, / Karlheinz Roth ; Bd. 2). http://doi.org/10.1007/978-3-662-08152-5.
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.
Suh, N. P. (1990), *The principles of design*. New York: Oxford University Press (Oxford series on advanced manufacturing, 6).
Suh, N. P. (2001), *Axiomatic design. Advances and applications*. New York, NY: Oxford University Press (The MIT-Pappalardo series in mechanical engineering).
Ulrich, K. T.; Eppinger, S. D. (2008), *Product design and development*. 4. ed., internat. ed. Boston: McGraw-Hill/Irwin.

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