UTILIZING THE EMBODIMENT FUNCTION RELATION AND TOLERANCE MODEL FOR ROBUST CONCEPT DESIGN

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ABSTRACT

The early use of Robust Design (RD) supports the development of product concepts with low sensitivity to variation, which offers advantages for reducing the risk of costly iterations. Due to the lack of approaches for early evaluation of product robustness, the embodiment-function-relation and tolerance (EFRT-) model was developed, which combines the contact and channel approach and tolerance graphs. The information exchange of both approaches offers a high potential for reliable robustness evaluation results. However, that potential currently relies unused, since the link between applicable robustness criteria and the extended information is missing. To solve this problem, four research steps were determined: (1) understanding of robustness, (2) collection of RD principles, (3) identification of EFRT-model information and (4) mapping of RD principles and information. The results show nine adapted RD principles, the identified model information for the robustness evaluation, the evaluation criteria as well as their mapping. Utilizing the mapping and the proposed criteria in this contribution, a more comprehensive robustness evaluation in early stages is enabled.

Keywords: Robust design, Conceptual design, Product modelling / models, Variation Management, Contact and Channel Approach

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1 INTRODUCTION

Robustness describes the insensitivity of products or processes to various sources of variation (Taguchi et al., 2005). The use of Robust Design (RD) in the early stages of product development offers potential for increasing product development efficiency through reducing iterations caused by later concept change. This is especially relevant for design decisions made in concept development, since they define the majority of the later product costs, e.g., in manufacturing (Ullman, 2010). So far, however, approaches of RD can only be taken into account late in the design process, as they require detailed product data as input (Davidson, 2007). Approaches for early evaluation of robustness in product development are still lacking (Gremyr and Hasenkamp, 2011).

In the design domain, understanding the embodiment function relations (EFRs) can be useful for the robustness evaluation of a product, since they describe how the embodiment design influences the function fulfilment of a product (Matthiesen, 2011). Approaches like Axiomatic Design (Suh, 1998) and Characteristics Properties Modeling (Weber, 2014) map the product's embodiment and functions. However, their utilization needs established design parameters, which are difficult to determine in the early stages. Instead, qualitative models like the Organ Domain models (Andreasen et al., 2015) or free sketches (Pahl et al., 2007) are used in the early stages for ideation, which cannot be directly utilized in RD tasks. A qualitative modelling approach that has already been applied to tasks of systems robustness, is the Contact and Channel Approach (C&C²-A) (Matthiesen and Ruckpaul, 2012; Grauberger et al., 2019). Tröster et al. (2021) show the possibility of using C&C²-A to model EFRs of different variations on the example of a single-disc dry clutch. However, the use of the information from C&C²-A for RD and robustness evaluation remains to be explored.

In the tolerance domain, this issue has been addressed through graph-based approaches, e.g., by Johannesson and Söderberg (2000) or Ballu et al. (2006), they depict information on an abstract level and aim at the traceability of RD decisions. Their application in the evaluation of robustness is limited, as they are missing elements to model specific design information, e.g., relations of embodiment and system behaviour or function. A graph-based approach that considers details of the product concept design is the tolerance graph (Goetz et al., 2018), which enables a detailed analysis of the product regarding its robustness. However, its applicability is limited in complicated systems, as no state-dependent design parameters are considered yet.

In summary, existing approaches of the design and tolerance domains show an insufficient link between and especially within approaches in early development stages, which hinders a sufficient robustness evaluation. As a result, the assessment of robustness using these approaches focuses on a specific aspect of a product whilst other robustness indicators may not be satisfied.

1.1 The embodiment function relation and tolerance model

Motivated by this aspect, Grauberger et al. (2020) present an initial concept enabling a combined robustness evaluation with models and information from two different approaches. As a basis, the graph-based tolerancing approach developed by Goetz et al. (2019) was used, since it defines a general framework for early robustness evaluation. It is based on graphical product sketches, which were identified as a feasible link with the C&C²-A. Modelling in the C&C²-A is also based on graphical sketches and is used as an ideation method for analysing the EFRs. Resulting from the connecting of both approaches, new insights could be identified, which were utilized for robustness evaluation. These insights were then used for concept improvements regarding its robustness focusing on the EFR (Grauberger et al., 2020). Based on that initial concept, Horber et al. (2022) developed the embodiment function relation and tolerance (EFRT-) model. Resulting from the fact, that both approaches rely on graphical models, a unifying model combination was developed. As the contents of the combined models are of high interest for this work, they will be analysed in more detail in section 3.

1.2 Research question

Through the EFRT-model, product developers are able to map and store information such as state-dependent properties and characteristics and retrieve them for evaluation. As mentioned, all information from the tolerance graph can now be used in the C&C²-A and vice versa, which enables a broader foundation for robustness evaluation.

The problem is, that this potential remains currently unused, since the link between applicable robustness criteria and the extended information in the EFRT-model is missing. Thus, the benefits of the model combination beyond the computer-processability through the SysML-based implementation proposed by Horber et al. (2022) are limited. Resulting from that lack, this contribution deals with the following research question:
How can the EFRT-model be utilized in order to enable the combined robustness evaluation and extend the existing capabilities of the current approaches?

2 RESEARCH APPROACH

To answer the research question, the research approach within this contribution consists of four systematic steps. An overview is given in Figure 1. The steps are described in detail in the following.

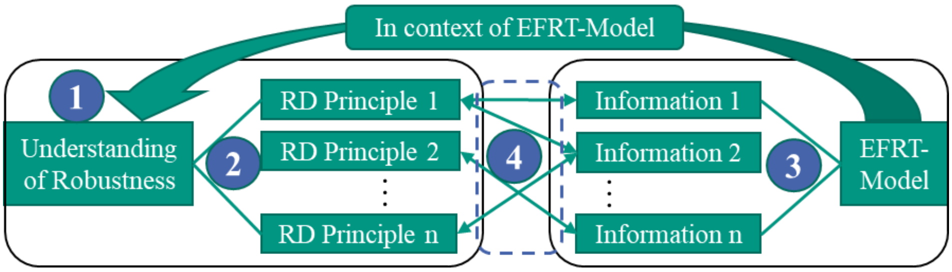

Figure 1. Overview of the research approach comprising four steps

Understanding of Robustness (1) in the early stages and for early robustness evaluation: Relevant definitions of robustness derived from the state of the art are evaluated regarding their applicability along with the EFRT-model. Sharpening the definitions from the state of the art may be necessary in order to comply with the information in the EFRT-model, which are feasible for robustness assessment.
Collection of RD Principles (2) for derivation of criteria used in robustness evaluation: The sharpened understanding is used to identify existing RD principles that can be used for the robustness evaluation. Existing RD principles, like shortening of force-transmission paths, have to be transferred into feasible criteria for the decision model (Goetz et al., 2018).
Identification of EFRT-Model Information (3) for combined robustness evaluation: In this step, a detailed analysis of the contents in the EFRT-model was conducted. The model contains many different types of information, which might be of interest for the evaluation of robustness. The different types of information need to be analysed in order to determine their relevance.
Mapping of RD Principles and Information (4) within the EFRT-model: The RD principles from step 2 are mapped to the information derived from the EFRT-model (step 3). This enables the link between information and robustness criteria. As an initial proof of concept, the resulting criteria and mapping are then applied to a use case.

3 RESULTS - CONNECTION OF INFORMATION AND RD PRINCIPLES

In the following, the results derived from the application of the research approach are described.
For the **understanding of Robustness** (1), it is necessary to define what should be insensitive and against which variations should the system be robust. Since the first introduction of robustness by Taguchi, a high number of definitions for robustness or RD have been published. Box and Fung (1994) describe robustness as insensitivity to variation. Taguchi divides the RD process into three stages: system design, parameter design and tolerance design (Taguchi et al., 2005). It is emphasized by Arvidsson and Gremyr (2008) that RD can be applied in all stages of product design. Hasenkamp et al. (2009) define the aim of RD as achieving both product and process insensitivity to variation. In contrast, Suh (1998) and Eifler et al. (2013) describe the target of RD as satisfying the functional requirements or performance. In turn, Phadke (1989) and Tsui (1996) consider not only the product quality but also the low product cost.
In context of the EFRT-model, the approach focuses on the early design stages and therefore mainly the product concept insensitivity is evaluated, while process insensitivity will not be taken into account.

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In Taguchi's approach the setting of control factors can make the product insensitive to variations in the noise factors, which have three types: outer noise (e.g., temperature), inner noise (e.g., wear) and between product noise (Byrne and Taguchi, 1987). Hasenkamp et al. (2009) define that the sources of variation or noise factors can be various. Gremyr (2011) considers the variations from manufacturing to customer usage, and degradation over product life. While some definitions (e.g., Tsui (1996)) focus on the manufacturing and environmental variations, the variation in product design such as changes and tolerances in design parameters are considered for insensitive design (Eifler et al., 2013; Suh, 1998).

In context of the EFRT-model, model information is considered as control factors, as they are used to adjust the product design. It has to be clarified that the geometric deviation, e.g., change or tolerance in design parameter, is considered as a control factor in the later stages like parameter or tolerance design. However, in early development, such information is not yet determined. Therefore, geometric deviation is considered as a noise factor and the product concept should be insensitive to this variation. Besides that, in the context of the EFRT-model, the modelling of EFRs and system states helps to evaluate the effect of the noise factors on the concept. As a consequence of the lack of quantitative information and low information depth in the early product development stage, experience-based principles for RD have been established (Goetz et al., 2019).

Due to the diversity of definitions of robustness, the result for the **understanding of Robustness** (1) in the present contribution is as follows*: robustness in early stages of development means that qualitative information in the product concept must comply with various rules and principles to achieve the insensitivity of the product concept to variation in the later lifecycle stages.*

Based on this definition of product robustness, a process including the EFRT-model as a foundation for evaluating concept robustness is derived as depicted in Figure 2.

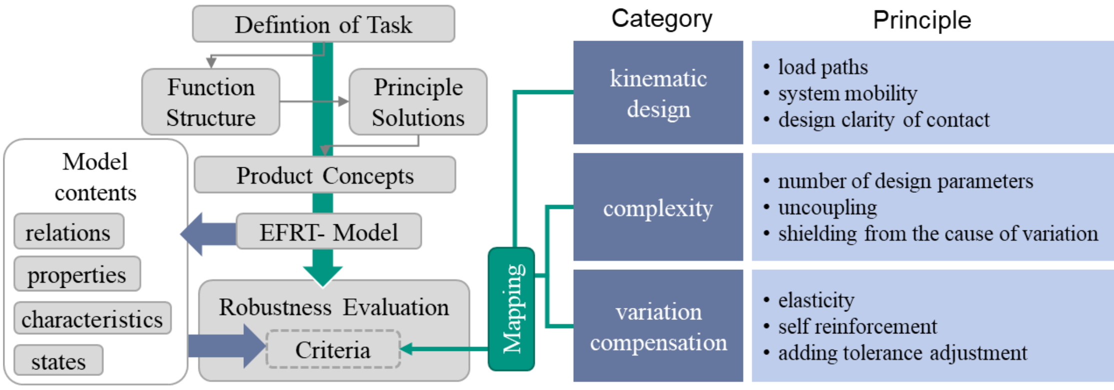

Figure 2. Robustness evaluation of product concepts utilizing the EFRT-model and criteria based on RD principles adapted from Goetz et al. (2019)

Starting with the definition of task, where product requirements are defined, the function structure and principle solutions can be developed. A combination of different principles enables the derivation of multiple viable concepts, which can be evaluated according to their individual robustness. Before that, the EFRT-model is modelled for the product concepts and their states using graphical tolerance graphs and C&C²-models in the proposed process first. It includes several pieces of information, e.g., relations, properties and characteristics of the parts and geometry elements as well as working surfaces and system states. That information is valuable for the assessment of criteria fulfilment in the robustness evaluation. Those criteria are adapted from the main RD principles as summarized by Goetz et al. (2019). The mapping between the information included in the EFRT-models and those principles are needed for criteria derivation and is part of the following step.

Collection of RD principles (2): Goetz et al. (2019) divide the robustness principles into three categories: kinematic design, complexity and safety. Within the present contribution, this collection was expanded with an additional category focusing variation compensation. In this category, the system behaviour under changed states is particularly to be considered. Since the assessment for category safety usually bases on other criteria, such as redundancy, the principles are not the focus of this contribution and will not be further discussed. The categories and principles have been adapted for the EFRT-model in the right part of Figure 2.

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In the **identification of EFRT-model information** (3), the EFRT-model is analysed regarding its content and the information, that is retrievable after the combination of the tolerance graph with the C&C²-A (see Figure 3). The tolerance graph consists of the assembly and part information based on the given product concept. Those single parts in the assembly can then be extended by semantic information and described by a set of geometry elements (GEs). For robustness evaluation, there are several information in this part of the EFRT-model, e.g., the interfaces of parts and the relation of GEs. GEs consist of parameters and the relation of GEs can be extended by tolerances (Goetz et al., 2018). They can be used for robustness evaluation with respect to geometrical variations or for example variations through temperature changes. So, the coefficient of expansion could be stored as a property of a part alongside its material.

Analysing the C&C²-Model reveals that mostly the working surfaces (WSs) and working surface pairs (WSPs) store information for robustness evaluation. The definition of properties, which are in that context surface-based, is a foundation for robustness evaluation. In contrast, the properties of channel and support structures (CSSs) are related to the structure. Besides that, the C&C²-Sequence Model enables the identification of critical system states and the consideration of this information in the robustness evaluation, which was not intended with the robustness evaluation based on only the tolerance graphs.

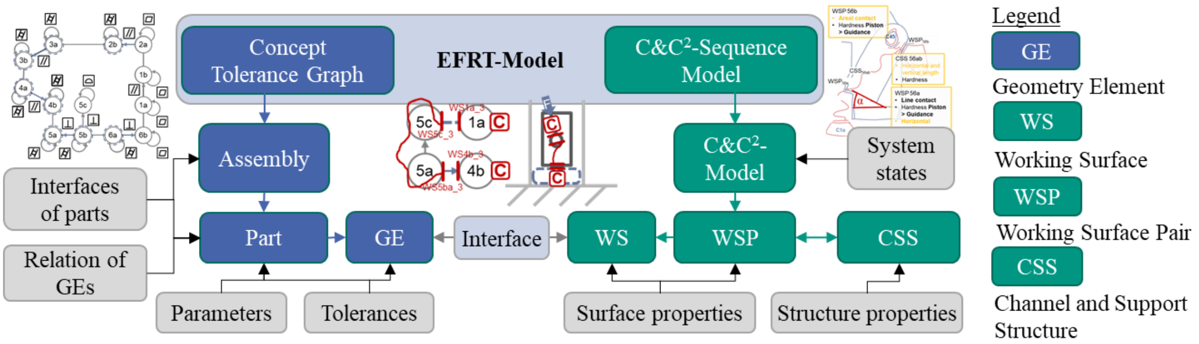

Figure 3. Summarized contents and information of the EFRT-model for a mechanical system as proposed by Horber et al. (2022)

Comparing elements of both approaches, resolution increases in the order: assembly, part, GE and WS. While in assembly the overall functionality of the system is considered, WS and WSP focus on the details on interface level. Hence, the EFRT-model can achieve a higher resolution than tolerance graph and C&C²-A alone. Some information can be stored in different elements of the EFRT-model, especially in the function relevant element GE, WS, WSP and CSS. The geometric information from the surfaces such as length or diameter is preferably stored in GE, while other physical parameters from the surfaces such as hardness, roughness should be stored in WS, since that information could be needed for the contact interactions which are stored in WSP, e.g., hardness difference or the coefficient of friction. Structure-based information that is relevant to the load paths is preferably stored in CSS, e.g., elasticity.

This preliminary summary of the EFRT-model information is now detailed for the further step **Mapping the information** (4). The results of this step contain three tables including evaluation criteria that were derived from the preliminary work and discussed by the authors. The details of the step are described in the following, which is structured by the categories of RD principles: **kinematic design**, **complexity** and **variation compensation**. The first column describes the principles adapted from Goetz et al. (2019). In the second column, the available information from the EFRT-model is explored and summarized. The third column lists criteria for early robustness evaluation according to the RD principles.

Kinematic design: The category kinematic design consists of three principles and is shown in Table 1. The principle *load paths* can be detected with C&C²-A and tolerance graphs. The length of the path can be measured through qualitative length differences of the CSS between concepts in criterion C_{K1}. For this, load paths are identified and their length is measured and normalized. Since the WSs are assigned to GEs, paths can also be identified between relevant GEs in the tolerance graph, hence the number of GEs in the paths can be counted for criterion C_{K2}. Robustness is assumed to increase with shorter paths (Andersson, 1997).

The principle *mobility of systems* is assessed through tolerance graphs. Here, the constraints on assembly level are considered. For that, the joint types from the tolerance graph are used. Each joint type restricts certain degrees of freedom, the system mobility can be calculated in criterion C_{K3} through the Kutzbach-Gruebler equation (Ebro et al., 2012). Robustness is assumed to decrease with overconstraintness. However, in case an overconstrained system is unavoidable, it is recommended to use the principles in the category variation compensation.

Table 1. Principles and criteria of the category kinematic design

Principles	Available information with model source	Criteria
Load paths	**TG:** length of path between relevant GEs **C&C²-A:** length of CSS	C_{K1} Qualitative length comparison C_{K2} Number of GEs in load path
System mobility	**TG:** joint type; Degree of freedom	C_{K3} Mobility on system level
Design clarity of contact	**TG:** contact of GE in the graph **C&C²-A:** number and location of WSPs in C&C²-Sequence Model; Clearance in WSPs; Limitation of WSP by component geometry	C_{K4} Constraintness on interface level C_{K5} Complexity of the contact of GE in graph C_{K6} Potentially undesirable WSP

TG = Tolerance Graph   C&C²-A= Contact and Channel Approach C_K =Criterion of Kinematic Design

Criteria C_{K4} to C_{K6} address different measuring possibilities of the principle of *design clarity of contact*. In this principle, the focus is shifted from the system level to the interface level, i.e., contacts between parts. Criterion C_{K4} assesses the constraint on interface level. Since the Kutzbach-Gruebler equation cannot be applied directly (Ebro et al., 2012), each individual interface between GEs should be analysed. The C&C²-A supports identifying overconstraintness of contacts since the achievable resolution is higher. For that, as few parallel WSPs in one GE as possible should be activated in one system state. Otherwise, the contact in the state cannot be clearly defined. This leads to overconstraintness on the interface, increases the variation in functional performance and affects the robustness. The unnecessary constraints on interface level can be removed, e.g., by adding clearance. Criterion C_{K5} checks the contact complexity of GE in the graph, e.g., a prismatic guide has more GEs and contacts than a cylinder guide in the tolerance graph. The aim is a simple contact that ensures functional fulfilment. Criterion C_{K6} checks for emerging WSPs in different system states. Surface deviation on the interface may cause change of WSPs position, which can become undesirable. Other problems could be the ambiguity of contact or collision when changing states. The physical properties of WSPs should also be considered as these could cause deterioration such as wear over time.

Complexity: The category complexity consists of three principles and is shown in Table 2.

Table 2. Principles and criteria of the category complexity

Principles	Available information with model source	Criteria
Number of design parameters	**TG:** design parameters in GE **C&C²-A:** design parameters in WSP, CSS	C_{C1} Number of parameters that are relevant for the function fulfilment
Uncoupling	**TG:** paths for different KCs through GEs **C&C²-A:** participating WSPs and CSSs in functions as well as their assignment to the components	C_{C2} Number of overlapping GEs involved in the KCs C_{C3} Number of paths for one KC C_{C4} Number of C&C² elements related to the same part relevant for a function
Shielding from the cause of variation	**C&C²-A:** properties in Connector (C) for system environment, properties in the system that result in undesirable functions and behavior	C_{C5} Effect of the shielding measure according to the properties in the design area and environment

TG = Tolerance Graph   C&C²-A= Contact and Channel Approach C_C=Criterion of Complexity

The principle *number of design parameters* addresses the parameters assigned to the elements of the tolerance graph and C&C²-A, e.g., a GE cylinder can have a parameter diameter, which would be counted in criterion C_{C1}. Those parameters are contained in the chain of elements, which are relevant for function fulfilment. The number of design parameters should be minimised since they are prone as a source of variation.

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The principle *uncoupling* is based on Axiomatic Design, where robustness of a system decreases from uncoupled to coupled systems (Suh, 1998). *Uncoupling* addresses the defined functions from earlier development activities, e.g., function structure development. For variation management, key characteristics (KCs) are derived from the most important functions for a system (Goetz et al., 2019). In tolerance graphs, a KC can be depicted as the connection between two GEs and is often defined by several paths with different lengths. Criterion C_{C2} checks the number of overlapping GEs involved in the KCs. Criterion C_{C3} counts the number of paths for one KC. The number should be minimised for an uncoupled design. The tolerance graphs focus on the geometric requirement, while the C&C²-A models focus on the interaction of parts during function fulfilment. Criterion C_{C4} evaluates the robustness of concepts according to the number of C&C² elements related to the same part relevant for a function. Multiple C&C² elements in a single part result in coupled design parameters. Therefore, robustness is assumed to increase with minimisation of the participating elements.
The principle *shielding* influences the sensitivity to outer noise, e.g., heat or humidity. Here the properties in WSPs and CSSs, that are critical to the external variation, should be analysed. The properties in the system environment are modelled in the connector element of the C&C²-A.
Variation compensation: The category variation compensation consists of three principles and is shown in Table 3.

Table 3. Principles and criteria of the category variation compensation

Principles	Available information with model source	Criteria	
Elasticity	**C&C²-A:** elasticity of CSS; length change of CSS	C_{V1}	Effect of the elasticity of CSS on function fulfilment by changing state
Self reinforcement	**C&C²-A:** reinforcing properties in WSP; Change of the load path under pressure in CSS	C_{V2}	Change in CSS
Adding tolerance adjustment	**TG:** additional GEs for tolerance adjustment **C&C²-A:** additional CSSs and WSPs	C_{V3}	Trade-off between manufacturing cost and assembly cost

TG = Tolerance Graph C&C²-A= Contact and Channel Approach C_V=Criterion of Variation Compensation

The principle *elasticity* addresses the compensation of overconstraintness in a system. There is no difference in a tolerance graph when a part is elastically deformed, while the length of CSS changes. Criterion C_{V1} determines the effect of this change through system state modelling with the C&C²-A. Elasticity can save costs by reducing tolerance requirements, but also leads to higher deflections. The trade-off between flexibility and deflections should therefore also be evaluated.
The principle *self-reinforcement* compensates for the variation of the external load. The reinforcing properties such as wedge effect can be modelled in a WSP. Criterion C_{V2} focuses the change of the CSS in the system state modelling, if the load path branches under pressure. For a robust concept, the CSS should not branch by changing state.
The principle *adding tolerance adjustment* compensates the manufacturing-induced variations. For example, a common method in industry is using shims for tolerance adjustment. In order to enable the later calibration, this needs to be planned during embodiment design. These adjustments can be depicted both in the tolerance graph and in the C&C²-A. Criterion C_{V3} evaluates the trade-off between manufacturing cost and assembly cost, which are dependent on the number of pieces.

4 APPLICATION TO THE COINING MACHINE USE CASE

In this section, three examples for the mentioned criteria (see Tables 1-3) are compared and evaluated, which were applied to a coining machine. The coining machine is a stamping mechanism driven by a manual crank lever, while the raw coin is imprinted through rotation of the crank. This use case has already been detailed by Horber et al. (2022) regarding the development of the EFRT-model. Therefore, only a short introduction is given in the following for understanding purposes (see Figure 4 top part). The system states of the coining machine are defined by the crank rotation and can be modelled individually with corresponding EFRT-models (Horber et al., 2022). Starting with state 1, the stamp is in its downstroke and is guided by a cylindrical guide. State 2 describes the first coin contact, state 3 the actual coining process, where the stamp flattens the coin. State 4 is the moment of release, while the stamp still has contact to the coin. State 5 describes the upstroke of the stamp.

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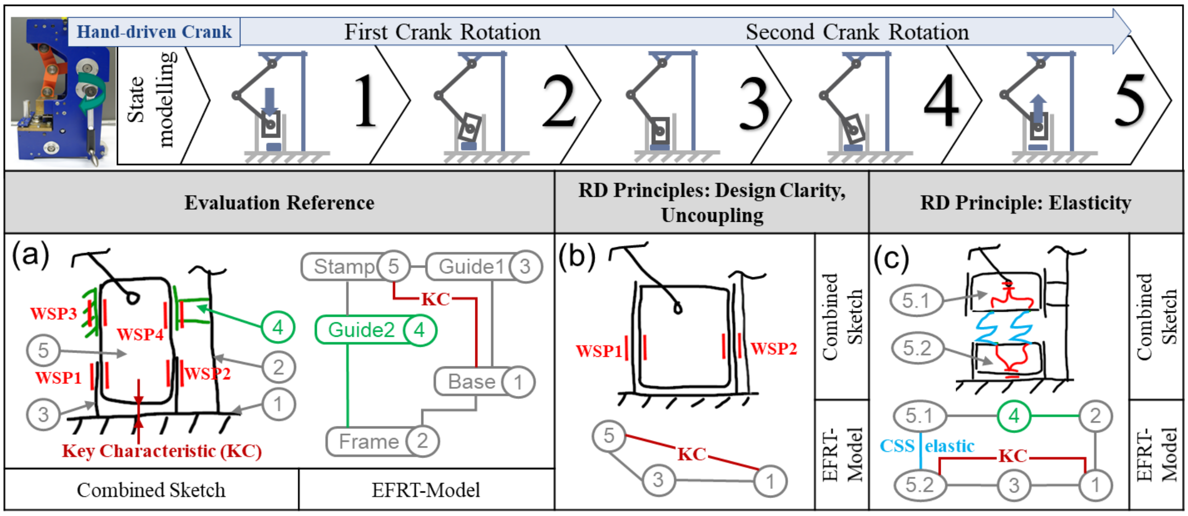

Figure 4. Application of mapping between robustness principles and information in EFRT-model using the example of a coining machine.

As a starting point, the reference concept (a) for the robustness evaluation is shown in Figure 4 (left side). In this concept, the combined sketch of the coining machine shows the base (1), the frame (2), two guides (3, 4) and the stamp (5). For improved understanding purposes, those product parts are not divided any further into one or multiple GEs, and the area of interest is limited to the function 'guiding stamp'. The combined sketch and the EFRT-model of this area are depicted for the evaluation. Analysing the model of the evaluation reference, the contact of the stamp respectively the activated WSP shows, that the contact is not clearly defined. Instead, it is overconstrained on interface level. This can possibly lead to jamming in some configurations, when tolerances are not managed properly. The parallelism between the bottom of stamp and the bottom frame contributes significantly to coining quality and forms a KC of the machine.

An alternative concept (b) with only one guide is shown in Figure 4 (center). The combined sketch shows that this concept has fewer potential WSPs than the evaluation reference (a) during the guiding, the jamming problem can therefore be solved. Based on criterion C_{K4}, this leads to the conclusion that concept (b) is more robust. Comparing the EFRT-models of both concepts, the contact of the cylinder surface of the stamp in (a) is more complicated, here the criterion C_{K5} can be used. Considering the principle uncoupling, the KC in (a) is involved in two paths in the area of interest, while in (b) it is only involved in one path. With focus on the C&C²-A, in concept (a), additional CSSs and WSPs related to the stamp must be considered. Therefore, according to criteria C_{C3} and C_{C4}, concept (b) is more robust than concept (a).

In some cases, two guides are desired for other reasons, e.g., a lower guide with smaller clearance to ensure accurate guiding, and an upper guide with more clearance to endure the coining force. For this, in concept (c) in Figure 4, right side, additional elasticity is added between the upper (5.1) and lower part (5.2) of the stamp. This addresses possible variations regarding the concentricity of the guides. As described before, the concept (a) is overconstrained on interface level. With the elasticity, this overconstraintness is compensated, while KC is still determined by the same path length. Therefore, the robustness of the concept is improved according to criterion C_{V1}. Thus a comparison between two concepts in an early stage of product development is possible.

5 DISCUSSION

Based on the results, the research question "*How can the EFRT-model be utilized in order to enable the combined robustness evaluation and extend the existing capabilities of the current approaches?*" can be answered as follows: through the derived criteria based on modelling elements of the EFRT-model and RD principles, the foundations for a comprehensible robustness evaluation in the early stages of product development are enabled. This was shown within the application to the coining machine use case, however, the improvement has to be investigated within empirical studies in future.

Resulting from the analysis of various definitions, robustness in the early stages is defined more precisely in this paper within the context of the EFRT-model. For example, the control and noise factors from Byrne and Taguchi (1987) are narrowed to the early stages due to the available information. As initially conceptualized by Grauberger et al. (2020) and developed further by Horber et al. (2022), the linking of the tolerance graph and C&C²-A can now be used to enhance the exchange of information between both approaches and for its use in a combined robustness evaluation. The criteria described within this contribution are based on the composition proposed by Götz et al. (2019), where different RD principles for robust concept design are feasible. In contrast to the described application of the principles in the literature, e.g., design clarity in Ebro et al. (2012), this paper focuses on how to represent the required information through modelling. Moreover, evaluation criteria are derived for the principles so that a more precise evaluation can take place. Compared to Horber et al. (2022), the use of the information from C&C²-A for RD and robustness evaluation has been explored. Although this information is now available, the information retrieval is currently done manually by the users. For later use in practice, an assisting tool for automated retrieval needs to be developed.

A challenge for the robustness evaluation utilizing the EFRT-model is, that some principles in the three categories may contradict each other. For example, division of functions or adding tolerance adjustment leads to a longer path in the tolerance graph and more design parameters to be considered. Therefore, a limitation of this research is, that it does not dissolve this challenge. An additional weighing function might support here in future. This might be challenging, as on one hand, a comparable robustness evaluation is needed, while on the other hand, different types of criteria might have different influences on the overall robustness of the product. The selection and weighting of RD principles as well as their evaluation must therefore be adjusted individually. Weighting is mostly determined based on product developers' experiences. Another limitation is the focus of the EFRT-model on mechanical system parts. As its underlying models are mostly used in investigation of physical components and system parts, it has to be enhanced with robustness evaluation methods of other domains like information technology or electronics to verify the robustness of mechatronic products.

6 CONCLUSION AND OUTLOOK

Motivated by the unused potential for robustness evaluation with the EFRT-model, this contribution explored the missing link between applicable robustness criteria and the extended information from the tolerance graphs and C&C²-A. To answer the research question, four steps were defined and carried out. In step 1 the understanding of robustness in the early stages of product development was improved. In step 2 three categories and nine RD principles were collected and presented. In step 3 both tolerance graph and C&C²-A are analysed to identify the relevant information for the robustness evaluation. Derived from this analysis, it was clarified which information can be stored in and retrieved from the different elements of the EFRT-model. In step 4, the mapping between RD principles and the information in EFRT-models is conducted, where one or more criteria have been proposed for each principle. The criteria were exemplarily applied to a coining machine use case, which shows, how the extended information from both approaches can be used for robustness evaluation in early stages of product development according to the derived criteria.

In summary, the proposed approach enables the exchange of information between the C&C²-A and tolerance graph. Utilizing the mapping and the defined criteria in this contribution, a more comprehensive robustness evaluation in the early stages of product development is now enabled.

As a next step, a novel process for weighting the principles should be developed, to enable the evaluation concerning multiple principles. In further work, it will also be investigated how an operationalized robustness index can be derived with the EFRT-model information considering the different demands of new product development or product redesign.

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