NORDDESIGN CONFERENCE
REYKJAVIK, ICELAND, 12-14 AUGUST 2024

Robust Conceptual Design for a Robust Early Embodiment Design

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Abstract: Utilisation of Robust Design (RD) principles in early stages of product development can reduce costly iterations by identifying concepts that are less prone to functional losses caused by variations. Valuable implications can be drawn from those principles, which are currently not transferred to later stages. Motivated by that, the RD principles are studied with the EFRT-Model. The transferability of nine different RD principles to later stages is analysed with a variation simulation of an exemplary snap fit joint use case and discussed based on their utilisation on a four-point scale.

Keywords: Robust Design, Simulation Based Design, Embodiment Design

1 Introduction

Product development in current days is faced with several challenges, such as shortened development cycles. Therefore, new approaches and methods are motivated by being 'first time right' (Meboldt et al. (2012), e.g., to develop a robust product concept that is insensitive to variations when it is further developed (Taguchi et al., 2005). In this regard, approaches in Robust Design (RD) focus on that (Park et al., 2006; Sharma et al., 2021) and thereby often build their motivation on the influence of variations on the perception of a products quality (Pedersen et al., 2016). Benefits from early robust design on later stages are shown for example by Goetz et al. (2021), analysing the application of the independence and information axiom and its effects on robust parameter and tolerance-cost optimisation. For the application of RD in general, several methods, practices, tools and principles can be used (Hasenkamp et al., 2009). Even companies that are faced with multiple challenges from RD (Fazl Mashhadi et al., 2012) derive their own guidelines (Fazl Mashhadi et al., 2016). In a recent study, Eifler et al. (2023) report from use cases in different industry fields with their according challenges that come with the associated products that are still facing issues regarding RD. In order to ease the adaption of RD in companies, methodologies exist, for example proposed by Krogstie et al. (2015).

Regarding adoption of RD in industry, Eifler et al. (2013) identified three success criteria and one of them being the early-stage application. Since the cost of resulting design changes increase exponentially with progression of the development process, RD methods for early stages are favourable (Goetz et al., 2020). In concept selection, robustness can be a relevant criterion to be considered (Sols, 2015), but a holistic evaluation of concepts also requires the analysis of the products functional fulfilment (Grauberger et al., 2020a). For this, approaches from the tolerancing domain like Axiomatic Design can be used (Suh, 1998). Besides that, the Contact and Channel Approach (C&C-A) can be applied from the design domain to describe the embodiment function relations (EFRs), enabling the analysis of functions based on working surface pairs (WSP) (Grauberger et al., 2020b). The transition to embodiment design and gaining of more quantitative information enables further analysis of products concepts, as shown by Armillotta (2015). But especially approaches on the edge between concept and embodiment design are hindered by the shift from qualitative to quantitative information. Iterations forth and back in those stages therefore require a sufficient link between their models and information (Wynn and Eckert, 2017). Relating this to RD and according to Taguchi et al. (2005), a distinction is made between system and concept design as well as parameter design, which is conveyed to the approaches in this research field. Thereby, RD focused concept selection is often performed based on RD principles (Goetz et al., 2019), which require varying information with quantitative as well as qualitative characteristics, such as sketches. But a product's robustness is often determined by a close connection between concept and embodiment design. Such cases apply, for example, when a parameter change of those geometrical elements leads to unexpected contacts, which result in increased wear. In many cases, models in early stages of concept design do not include information from embodiment design that is required in such cases. In this regard, the existing RD principles are primarily aimed at establishing the most robust concept for the product, which is why transferability to later phases is unclear. This is especially necessary, when iterations in embodiment design affect concept decisions. Since this has not yet been investigated, the research question for this contribution can be formulated as follows: *Which RD principles for concept analysis can be transferred to an early robust embodiment design?* As this investigation cannot be generally valid, the RD principles are analysed within a snap fit joint use case and implications to adapt the results to other use cases are given. The EFRT-Model is used for this analysis and the reason as well its foundations are briefly detailed in Section 2.

2 Preliminaries on the EFRT-Model

Research approaches in the field of RD addressing the system and concept design stage therefore focus on improving the robustness of a product as early in development as possible (Goetz et al., 2020). The product's behaviour is thereby often related to measures, often called Key Characteristics (KC), which represent specific requirements (Thornton, 1999), e.g., a required clearance between two parts. With the close interactions of functional fulfilment by the product concept and its embodiment, the EFRs are of high interest within robustness evaluations. Although there is a great importance of linking the tolerance and design domain, current models from both lack a sufficient link for their combined use in the conceptual design stage (Grauberger et al., 2020a). To solve this, Horber et al. (2022) developed the embodiment function relation and tolerance (EFRT-) model, which on the one hand combines graphical product sketches as well as model elements from the C&C-A to integrate EFRs graphically. On the other hand, the model is formalised based on the tolerance graph developed by Goetz et al. (2020) and enables product designers to describe the product structure with basic geometrical elements, such as cylindrical features, and add tolerance information as well as EFR information. The modelling method can assist as a thinking tool in order to bridge the gap between conceptual as well as embodiment design, as highlighted red in Figure 1. The method is used within the present contribution since the sole use of graph-based tolerancing and C&C-A leaves potentials by their combination unused. This results in a gap that can be closed with the EFRT-model, as it serves to formalize product concepts and can be used for robustness evaluations relating to existing RD principles. By that, it contains information from the early stages, in particular from product planning and conceptual design. However, the information content is not limited to this. The model can also contain specific values of a parametric model and therefore also covers sub-areas of embodiment design.

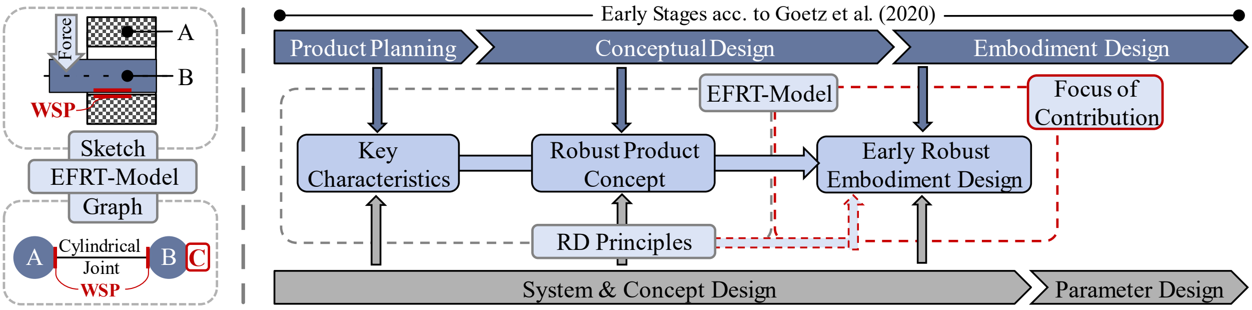

Figure 1. EFRT-Model (minimal working example on the left side) put into context of RD activities in early stages of product development according to Goetz et al. (2020) and derived focus of contribution (highlighted in red)

The model builds on the EFRT-Sketch and EFRT-Graph, both shown in the minimal working example in Figure 1 (left), which depicts a shaft (B) in a bearing (A) resulting in a cylindrical joint. The force applied to the shaft leads to two working surfaces (red lines), as shown in the sketch, which can also be paired to one WSP, as shown in the graph. In the latter, the external factors such as the force F can be included in the model via Connectors (C). Since the main focus of the model is the combination of qualitative and quantitative data from early stages of development, it can be utilised for different use cases. Such case is the robustness evaluation of product concepts, where RD principles are used as criteria to evaluate the estimated robustness of each alternative (Li et al., 2023). In this approach, the summarized RD principles by Goetz et al. (2019) are used. Accordingly, Li et al. (2023) discussed the nine RD principles and their applicability from a concept decision perspective, which are summarized in three categories. Category (1) 'kinematic' design summarizes load path, system mobility and design clarity. The category (2) 'complexity' focusses on the number of design parameters, uncoupling and shielding from the cause of variation. Lastly, category (3) 'variation compensation' concerns different kinds of compensation, which can be achieved by elasticity, self-reinforcement as well as the addition of tolerance adjustments. In the current state, the EFRT-Model can be used for the robustness evaluation, but the modelling activities are driven from a concept design perspective so far, although information from embodiment could be included. Therefore, potentials of the model and the RD principles remain unused.

3 Materials and Methods

The methodology to answer the research questions of this contribution consists of two main steps. First, the snap fit joint designs are analysed according to the model contents of the respective EFRT-Models. In detail, the RD principles in the context of concept design with the EFRT-Model described by Li et al. (2023) are applied to two different snap fit joint designs and the transferability of each principle is assessed (see Section 5.1). Second, the assessment of the transferability is analysed from a simulation perspective, focusing on whether the information gathered from the RD principles improve the creation process of the variation simulation model (see Section 5.2). For that purpose, a simulation of the snap fit joint was set up in order to analyse the holding force of different designs. The overall methodology is depicted in Figure 2.

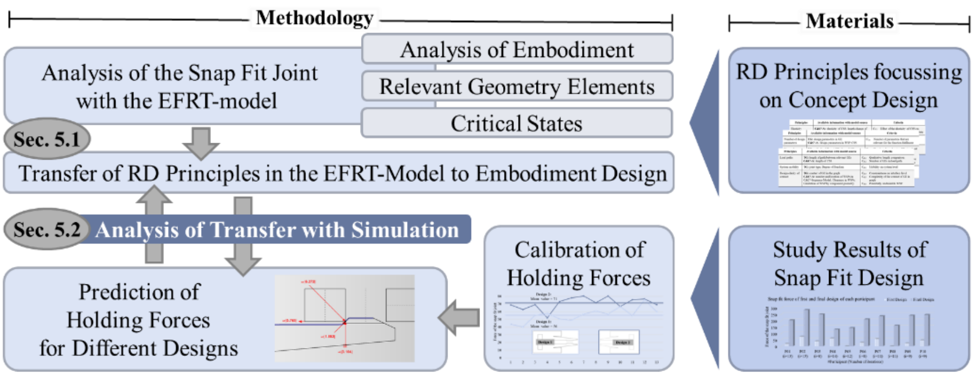

Figure 2. Methodology of the contribution (left side) and used materials (right side)

As the right side of Figure 2 indicates, the results of a previous study on the snap fit joint design are used to select the designs which are represented by the simulation model. In order to improve the understanding of this use case, the main aspects of the study performed by Liewerenz et al. (2023) are described. The snap fit joint design is an experiment performed by engineering students, where different designs can be established through a web-based computer-aided design platform by varying the embodiment design. As this study focuses on rapid prototyping, each design can be manufactured with a laser-cutter and tested regarding their holding forces right after that (see Figure 3a).

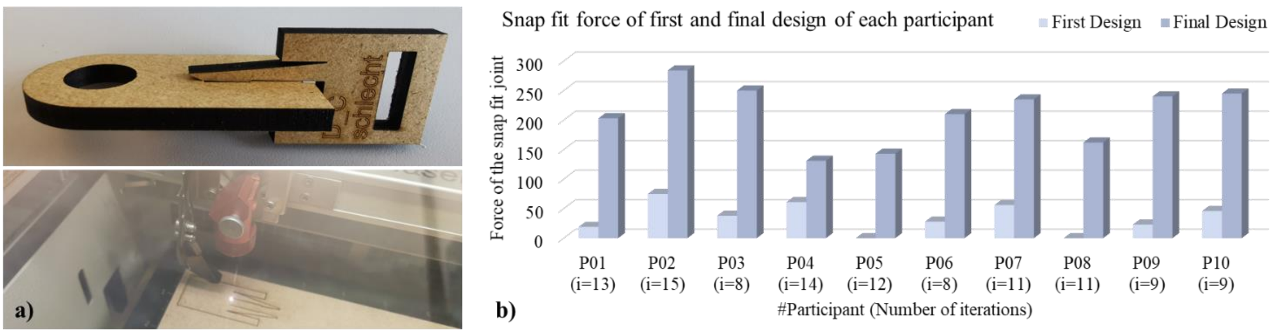

Figure 3. (a) Early prototyping of snap fit joints and (b) results of a conducted study on snap fit joint design by Liewerenz et al. (2023)

The main interest of the study lies on deriving specific design knowledge along multiple iterations for the snap fit joint design, resulting in rising holding forces from the first to the final design, see Figure 3b. For example, participant P02 started with a holding force of 75N and finished after 15 iterations with a holding force of the final design with 284N. As concluded by Liewerenz et al. (2023), one finding from the study is the success factor of running multiple tests with the same configuration with no modification, which can be traced back to manufacturing induced variations. Thus, considering the statistical effects of unavoidable variations, which are especially predominant in rapid prototyping in early design stages, is crucial. Since tolerancing is assigned to the late design stages and usually requires more precise manufacturing technologies leading to higher costs, RD aspects are particularly important in the early design stages to ensure the required functionality of a product.

4 Analysis of the Snap Fit Joint

The first step of the methodical approach includes the analysis of the snap fit design use case to build the fundamentals for creating the according EFRT-Models. In the literature, several different kinds of snap fit joints and design guidelines exist, such as from the company Bayer Material Science (2013). With the given use case of the snap fit design study, the basic concept is already selected, which follows the type of a cantilever snap joint (Bayer Material Science, 2013). Since the present contribution focusses on RD implications for an early robust embodiment design, the detail design of the snap fit joint is not targeted. For the analysis with the EFRT-Model it is necessary to specify the functions and the KCs of the design, which can be derived from the following requirements:

1. The snap fit joint shall be able to endure 200N of force before unclipping
2. The snap fit joint shall have minimal strain in the clipped-in state to reduce fatigue
3. The snap fit joint shall be designed in such way that the parts are not movable in the clipped-in state

The main KCs to fulfil those functional requirements can be derived: (KC1) Holding force, which should be maximised in the state before unclipping to meet the required value. Otherwise, it shall be minimized in the clipped in state to reduce fatigue effects introduced by remaining strain. (KC2) Clearance in the clipped in state. With those in mind, two different embodiment designs can be derived, which fulfil those requirements, but differ from each other on a conceptual level. Both are depicted in Figure 4, each in their idealised configuration and consisting of the snap fit body and the counterpart (naming convention is detailed in Figure 4).

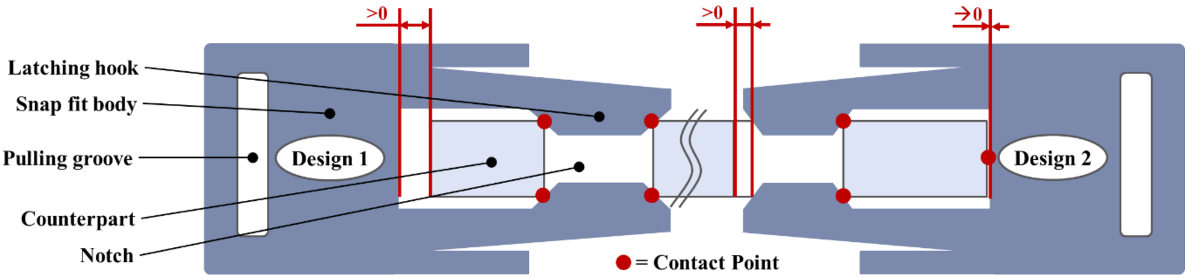

Figure 4. Two different embodiment designs of the snap fit joint design resulting in two concepts (including naming convention)

Assuming that the parameters of the latching hook are identical in both designs, the maximum holding forces of each design is the same as well as the remaining strain is zero in this idealised configuration. They mainly differ in their way to reduce the clearance in the clipped in state. Design 1 (Figure 4, left side) uses only the latching hook and the front and back surface of it to minimize the clearance, creating 4 specific contact points (Figure 4, red dots). For that, the distance between the snap fit body and the counterpart needs to be greater than zero to ensure that no unwanted contacts exist. Design 2 (Figure 4, right side) uses the front surface of the main snap fit body and the back face of the latching hook for this purpose, resulting in three contact points. To ensure the functionality, a gap between the notch in the counterpart and the latching hook is necessary. Both designs have the same parameters, but only differentiate from each other in their configuration. Depending on this configuration, the concept for limiting the movability can be achieved. Within the present contribution, this is referred to as “two different concepts”.

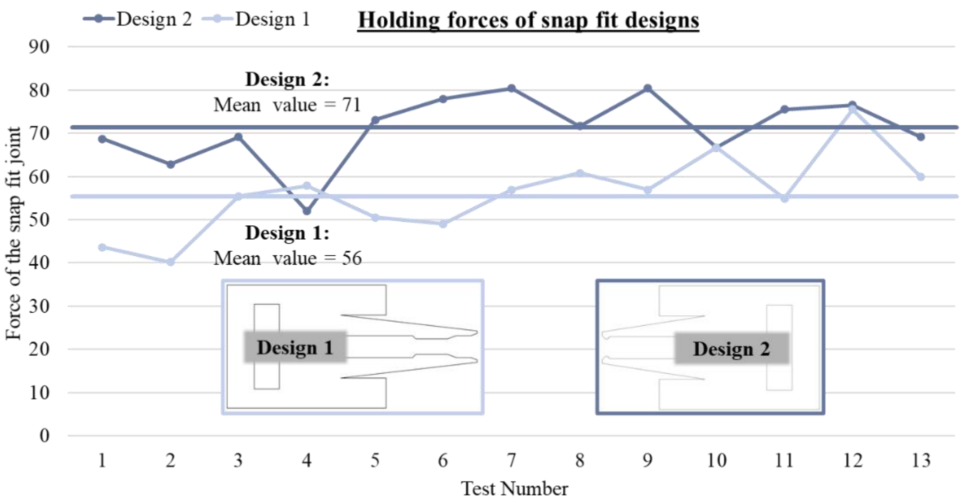

Figure 5. Holding forces of the tested batches of two different snap fit joint designs

Since the present contribution focusses on the transfer of theoretical implications from the EFRT-Model to the creation process of the simulation model and the results from the simulation, values for the actual holding force are needed to calibrate the model. Therefore, batches for both designs of snap fits were measured. The results are shown in Figure 5. Since the embodiment design of the snap fit designs are analysed in the next section in more detail, only the main implications are drawn from the diagram. Design 2 has a higher mean holding force of 71N, whereas Design 1 has a mean holding force of 56N. Besides that, initial indications about the spread of the holding force values are available.

5 Results

Based on those foundations, the results of the snap fit joint analysis with the EFRT-Model and the assessment of RD principle utilisation are given in Section 5.1. Section 5.2 then shows the results of the transfer of theoretical implications to the creation of the simulation model and the discussion (Section 6) lastly focusses on the transferability of RD principles.

5.1 Transfer of RD Principles based on the EFRT-Model

As Figure 4 shows, the clipped-in state is one of the critical states to ensure the functional compliance with the requirements. Klahn et al. (2016) refer to this state as "assembled" and divide the remaining states in "joining" and "during joining". For the use case in the present contribution, instead of joining, the separation of the snap fit joint from the assembled state is critical. In this state, the latching hook deflects and builds up the holding force to a maximum until the front part of the latching hook leaves the edges of the notch in the counterpart. This state is referred to as "unclipping".

With both critical states and the conceptual foundations in mind, the EFRT-Model can be created. Based on the implications of RD principles in EFRT-Models proposed by Li et al. (2023), each of them can be discussed accordingly. Beginning with *design clarity* and *uncoupling*, two different configurations of the snap fit joint can be identified, which are depicted in Figure 6 graphically as well as with their relevant section of the EFRT-Model. It has to be noted that, in order to improve comprehensibility, the following figures show the upper half of the joint since it is symmetrical.

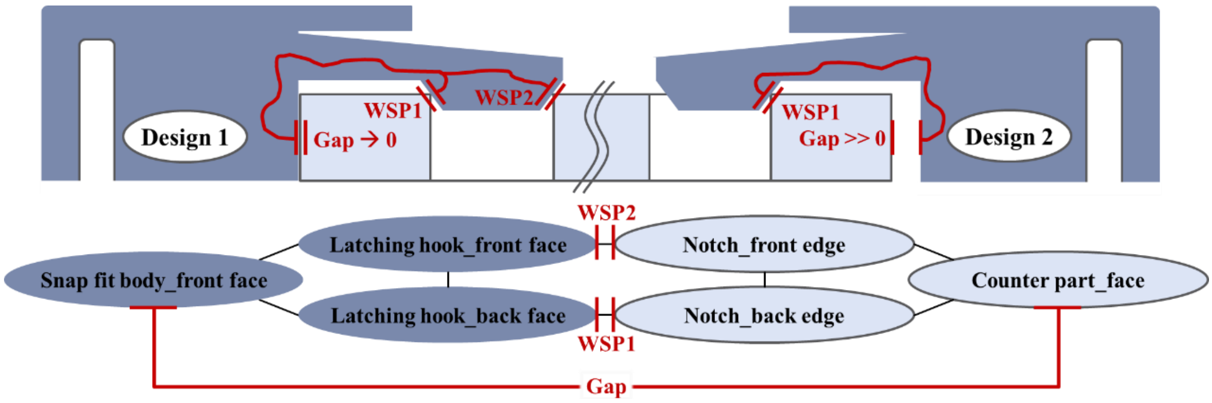

Figure 6. Graphical EFRT-Model of the two designs with issues regarding design clarity of contacts

Design clarity focuses on the number as well as location of WSP and includes any desired as well as undesired contacts. Clear contacts are therefore the goal when focusing in this RD principle. As shown with the critical configurations in Figure 6 (upper half), two cases can exist, which lead to unclear contacts (respectively WSPs). On the left side and in contrast to Figure 4, the configuration of design 1 results in three contacts, making it unclear which contact will be active in the real product. Due to manufacturing as well as other causes of variation, this leaves to a reduced robustness regarding the defined KCs, for example, when unwanted contacts lead to excessive wear. On the right side, the configuration of design 2 leaves a gap between the front surface of the snap fit body and the counterpart, which should be minimized as shown in Figure 4. By that, KC2 is unfulfilled since clearance in the clipped in state is noticeable. Additionally, the contacts may be unclear, since this clearance leaves enough possibility of movement of the parts to be out of contact. In order achieve a clear understanding of the contacts, enough space to compensate the variations according to the RD principle *adding tolerance adjustment* is feasible, as shown in Figure 4. This principle may also be applied to add compensating parts to the design, which is not focused within the snap fit joint use case.

Based on that analysis in the sketches of each design, the contacts (respectively WSPs) are integral part of the EFRT-Model. Together with the KCs, the RD principle *uncoupling* can be analysed in detail. *Uncoupling* focusses on the number of paths, which affect a KC. As depicted in Figure 6, the KC in design 1 is described by two different paths (WSP1 and WSP2), resulting in a reduced robustness. Accordingly, this can be also visualised in the EFRT-Model, where the product concept is formalised regarding its geometrical elements (Figure 6, lower half). In contrast to that, the KC in design 2 is only defined by one path including WSP1. Keeping the problems of this design with the RD principle *design clarity* in mind, this path can change between WSP1 and WSP2 depending on the actual position of both parts.

From the nine RD principles, a total of two are not utilised in the context of the snap fit design and its selected area of interest. *System mobility* assesses the degree of freedom in the system. Since the area of interest only focusses the two parts of the snap fit, no further joints are included. Extending the area to include further system context, e.g., the weight measurement, this principle would be assessable. Since only geometrical variations regarding the parameter configuration of each design are focused in this use case, the RD principle *shielding from the cause of variation* is also neglected.

The three RD principles *load path*, *elasticity* and *self-reinforcement* are now discussed along with the graphical representations of two different snap fit configurations in the unclipping state, as depicted in Figure 7. In this state, the snap fit body is separated from the counterpart, deflecting the latching hook and requiring the pulling force (F_{pull}). This is visualised with the C&C-A connector, which is used to integrate external information like forces into a sketch.

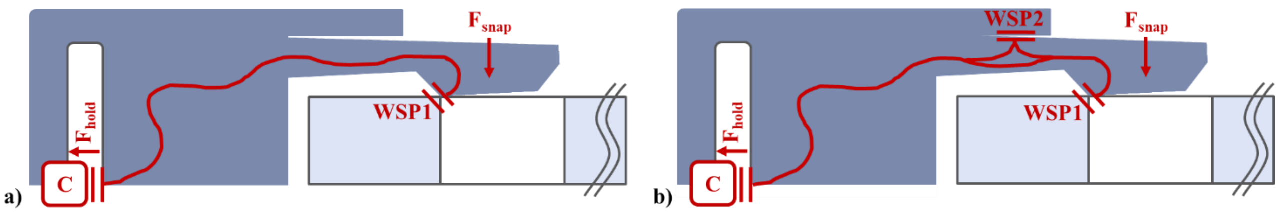

Figure 7. Graphical EFRT-Model of the snap fit in the unclipping state without self-reinforcement (a) or with self-reinforcement (b)

Both configurations (a & b) shown in Figure 7 rely on the RD principle *elasticity*. The intended holding force of the snap fit joint is thereby dependent on the stiffness of the latching hook. Together with its deflection, a force (F_{snap}) is build up at the WSP1, that counteracts the pulling force until the critical state is exceeded. By that, the RD principle elasticity is intended to compensate geometrical variations. The overall stiffness of the latching hook in both configurations is depended on actual geometry along the *load path*. The respective RD principle focuses on a short load path, leading to less impact of geometrical variations on the stiffness. However, the maximum deflection is also limited, which makes it necessary to find the best trade-off between load path length and functional fulfilment. Derived from that, the load path in configuration (a) is shorter than (b). This is due to the fact, that configuration (b) uses the RD principle self-reinforcement in form of an additional contact, which is applied when the latching hook deflects (WSP2). This creates an increase in stiffness and therefore a higher achievable holding force of the snap fit joint. Ideally, this principle is used intentional, but it can also occur unintentionally, when the latching hook gets into contact with the snap fit body. In practice, this increase might also lead to problems regarding longevity of the snap fit. Additionally, it has to be checked in detail design, whether the snap fit can be clipped in and out without jamming.

Lastly, the RD principle *number of design parameters* states, that less involved parameters ease the consideration of variations since long chains of connected parameters complicate the handling of variations. In the given use case of the snap fit joint, configuration (a) has less design parameters than (b). This is due to the fact, that the additional favoured contact for *self-reinforcement* in (b) requires the design to be manufactured in such way, that this contact is created in the exact place as planned. Deviations from that would lead to a decrease of the reinforcement effect or to unwantedly high forces that could lead to damage to the latching hook.

Table 1. Assessed utilisation of RD principles for the embodiment design of the snap fit joint (no: o, low: +, middle: ++, high: +++)

Robust Design Principle	Assessed Utilisation	Gathered Information from RD Principle in the Context the Snap Fit Joint Design
Load paths	++	Trade-off between shorter load paths and functional fulfilment
System mobility	o	Not utilisable in this scenario, since no joints are included that lead to unrestraint degrees of freedom
Design clarity of contact	+++	Clear contacts are necessary, which can be achieved by enough space to compensate variations
Number of design parameters	++	Less design parameters are in favour, but could contradict to other RD principles, such as self-reinforcement
Uncoupling	+	Coupling occurs in specific configurations of deviated geometry, which can be compensated with enough space to prevent from unwanted contacts
Shielding from the cause of variation	o	Not utilisable, since no additional parts should be added
Elasticity	+++	The concept relies on deflection of the latching hook, which can compensate variations
Self-reinforcement	++	Increase in stiffness through additional contacts resulting from the deflected latching hook
Adding tolerance adjustment	+	Provide enough space to compensate variations, but without additional adjustment parts

To sum up the findings from the theoretical analysis of the RD principles in the context of the EFRT-Model, the utilisation of each of the nine principles is assessed. This is summarised in Table 1. The gathered information was transferred to the simulation perspective, focusing on improving the creation process of the simulation model, as shown in Section 5.2.

5.2 Analysis of Transfer to the Simulation Perspective

The results obtained from the theoretical fundamentals of RD Principles in the context of the EFRT-Model show that there are several aspects, which can support the development of an initial embodiment design. Knowledge about the EFRs enables the identification of potential critical states, where impacts on the functionality of the snap fit joint are induced by geometrical variations, as shown in Figure 6. The two distinguished designs mainly differentiate from each other based on the configuration of parameters, which results in the two separate concepts. Based on the discussion of RD principles (see Table 1), the two implications can be drawn for the further analysis of both concepts: (1) Ensure clear contacts through spaces for compensation of geometrical variations and (2) trade-off between functional fulfilment and suggestions derived from the RD principles. The following potential causes of nonfulfillment in the clipped in state of KC1 (minimal strain) and KC2 (minimal clearance) caused by variations in the design can be derived with the theoretical perspective:

1. Depending on the configuration of parameters, the latching hook, which connects the snap fit hook and body, can get into contact with the counterpart resulting into remaining strain in the latching hook.
2. Increase in stiffness of the latching hook through unintentional contacts and use of the RD principle *self-reinforcement* can lead to unwanted defects of the joint or excessive wear
3. A trade-off between remaining clearance in the joint and minimal strain is needed, since both KCs cannot be minimised simultaneously and fulfilled individually

With those implications drawn from the theoretical perspective, the simulation model was created. For that, an initial study on the snap fit joint design was created in the two-dimensional variation simulation tool *Enventive Concept*. The resulting configurations from the web-based computer-aided design platform of the snap fit joint design study can be exported for manufacturing using the drawing exchange format and those files can be imported into the simulation tool as well. The fundamentals of setting up the simulation model are depicted in Figure 8 (a and b).

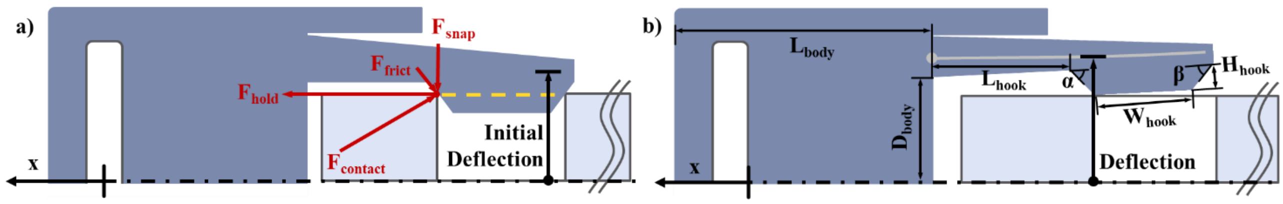

Figure 8. Fundamentals of the variation simulation model (depicted qualitative) to predict holding forces (a) based on the pulled distance “x” resulting in deflection of the latching hook (b)

Since the use case is intended to cover the early product development stages, an approach to simplify the model was conducted that limits the amount of effort placed into modelling the scenario. Therefore, the symmetries are used, as shown in Figure 8. In the simulation, the snap fit joint is separated along the line of symmetry (x). To calculate the holding force for one latching hook (F_{hold}), the force in the contact ($F_{contact}$) and the corresponding friction force (F_{frict}) is needed, which can be derived from the force of the latching hook (F_{snap}). The friction coefficient was set to 0.3, which is in the range of common values for wood (Aira et al., 2014). Both designs from Figure 4 are modelled with the same configuration of parameters, only varying the angle α as well as the hook width in order to realise both concepts of minimising the clearance in the snap fit joint. For each concept, the counterpart is set to two different lengths, but no geometrical variations are focused in this part. Together with the measured values of the real snap fit designs (see Figure 5), the measured holding forces can be used for calibration as well as calculation purposes. This is summarised in Table 2.

Table 2. Main differences between parameters of both designs and measured compared to calculated holding forces

Parameter	Design 1	Design 2
Angle α	45°	40°
Hook width W_{hook}	3 mm	4 mm
Measured holding force for calibration	71 N	56 N
Maximum holding force in the simulation	(70,88 N)	58,61 N

As mentioned, the calculation of $F_{contact}$ requires the force from the latching hook F_{snap}, which is a function of the stiffness of the latching hook multiplied by its actual deflection. In order to calibrate the model to the measured holding forces, the mean holding force (71N) from design 1 was used, which results in a stiffness of 50 N/mm and a simulated maximum holding force of 70,88N (value in brackets in Table 2 since it is used for calibration of the model). For design 2, the measured mean holding force of 56N results in a simulated value of 58,61N. Since this study does not focus any precise calculations of holding forces from different sets of parameter configurations, this accuracy is assumed to be sufficient. As shown in Figure 8 (a), each concept can have an initial deflection resulting in remaining strain in the clipped-in state, which needs to be minimised according to the KC2. Especially with the concept of design 2, this initial deflection may be limited by the width of the notch in the counterpart (as indicated with the yellow dashed line in Figure 8a).

The simulation shows that the evaluation of the first part of KC1 focusing on maximising the holding force before unclipping is the same for each design. The main contributors are: the height of the latching hook H_{hook}, latching hook length L_{hook}, snap fit body depth D_{body} and the angle α. For the discussion of the results, this state is therefore not of interest. Instead, the focus lies on the clipped in state and the results of the variation analysis of both designs in this state are summarised in Table 3. The variations in the model were defined as follows: linear dimensions ± 0,25 mm, radial dimensions ± 0,1 mm and angular dimensions ± 0,25 degrees. The method for variation simulations was set to be root sum square and the calculated sensitivities represent the effect of each contributor on the variation of the selected functional KC. In this case, the initial deflection was analysed. Since the simulation focusses only on an initial analysis of both design from a RD perspective, the information on the contributor is more of interest than the actual values of sensitivity.

Table 3. Contributors on deflection of each design in the clipped in state (x indicates that this contributor has no effect on a design)

Contributors on deflection (clipped in state)		**Sensitivities**	
		Design 1	**Design 2**
Latching Hook	Height H_{hook}	-1.0000	0.0094
	Length L_{hook}	-0.9552	-0.00004
	Width W_{hook}	x	0.3016
	Angle α	0.0167	-0.0038
	Angle β	x	-0.0088
Snap Fit Body	Length L_{body}	0.9554	x
	Depth D_{body}	0.0368	-0.0094

6 Discussion

As concluded from the simulation perspective, the main focus lies on the clipped in state and as concluded from the theoretical perspective with the EFRT-Model, the trade-off between remaining clearance in the joint (KC2) and minimal strain (KC1) is of interest for discussion. When the RD principles *design clarity of contact*, *uncoupling* and *adding tolerance adjustment* are followed and enough space is provided for variation compensation, both designs depicted in Figure 4 can be realised and enable a sufficient way to analyse both KCs with the simulation model and the comparison to the discussed RD principles in Table 1. Comparing the results from the contributor analysis to the analysis of RD principles with the EFRT-Model match the conclusions on the principle *number of design parameters* that less parameters are in favour. As shown in Table 3, a total of five contributors are relevant for design 1 whereas design 2 has six contributors, each with their individual sensitivity. Since this analysis is focused to enable a first robust embodiment design, as motivated with Figure 1, it can be concluded that design 1 is more robust than design 2. In general, the parameter configuration of each design should never be in such form that the over constrained cases in Figure 6 occur. This would lead to unclear contacts, e.g., through the coupling of different paths that describe a single KC. But for the actual parametrisation of the designs, the RD principle *load path* can be used to derive essential conclusions in accordance with the RD principle *elasticity*. The functional fulfilment regarding the maximum holding force (KC1) requires a trade-off between a short load path and the elasticity of the latching hook, which can be transferred to the simulation model, e.g., through limiting the deflection or stress in the latching hook as proposed in literature (Bayer Material Science, 2013).

The results of this study show that the analysis of RD principles with the EFRT-Model is a suitable approach when transferring from the concept design stage to an early embodiment design and especially when iterations between them occur. Different implications drawn from the theoretical perspective can be observed in the simulation perspective as well and can improve the modelling of potentially critical scenarios for their further analysis in the simulation. But it shows, that those RD principles are in some cases not independent of each other, e.g., *number of design parameters* and *adding tolerance adjustments*. Nonetheless, the EFRT-Model can be applied as a thinking tool before time-consuming modelling and simulation activities are initiated or in the case, where not enough information for creation of the simulation model is present, e.g., the product's embodiment. This leads to a gain in knowledge through iterating around the problem (Wynn and Eckert, 2017) by applying the RD principles in the model. Another benefit is that new potential configurations or critical states can be identified and analysed, which would require much effort when directly starting to model them in a simulation tool. Compared to setting up the simulation, the effort needed for the graphical models is lower. While creating the models can be performed in a few minutes, the time required for the analysis of the RD principles and the functional analysis is dependent on the complexity of the product as well as the engineer's experience. With that comes a limitation of the approach, which can be tackled by using this approach in a team of experts from the field of RD and even manufacturing. The analysed use case is two-dimensional, but the EFRT-Model builds upon the idea of reducing three-dimensional mechanisms into two-dimensional problems, but still storing the information in the model, e.g., spherical joints, in order to make it available in the analysis. Therefore, the method can be applied for mechanisms that can be represented as two-dimensional problems. If the complexity of the aspired concept is very high and the reduction of the whole mechanism is not applicable, the method still provides the possibility to shift or zoom in the area of interest for the analysis in such way that the new area of interest can be reduced in its dimension. This is due to the fractal character of the C&C-A, which is described by one of its three underlying hypotheses (Grauberger et al., 2020b). Currently, there is no general approach for this area of interest shift, which therefore requires more applications in complex use cases and the derivation of general rules. Resulting from the model nature of graph-based tolerancing and C&C-A, the EFRT-Model builds mostly on geometric KCs in order to describe and analyse the product's functions. Potentials from considerations of non-functional aspects remain therefore currently undiscovered, but offer inspiration for future research in this regard.

In this contribution, the approach was applied to the use case of the snap fit joint design. The basic concept was already defined by the study of Liewerenz et al. (2023), but several other concepts for a snap fit joint are available (Bayer Material Science, 2013). The focus did not lie on an iteration back to the concept decision, but was primarily targeted on the close dependency of parameter configuration and concept on a micro level, as shown with the designs in Figure 4. Besides the snap fit joint design, other use cases may also be relevant for this kind of scenario. For example, the design of linkage systems. With the current use case, it was not intended to do a validation of the variation simulation. Therefore, the measurements done in advance (see Figure 4) were only used for the calibration of the holding force. The reason for this was the trade-off between the scenario of early-stage development with the limited amount of product information and the efforts needed for modelling. Another aspect is thereby the focus on rapid prototyping of the snap fit joint, which includes manufacturing processes that are not ideal for exact manufacturing, such as laser-cutting the joints from wood. Therefore, the manufactured snap fit joints were not measured regarding their variations, such as the variation of the thickness of the wood, which would be necessary to validate the model. Additionally, simplifications in the simulation model were done to meet the compromise between modelling effort and accuracy. In the simulation tool, the stiffness of the latching hook was defined with a lookup table, but currently follows a constant value. In future, this could be improved with a finite element simulation of the stiffness, which results can be imported in the current model. Besides that, the friction coefficient of the used material needs to be validated as well, since currently a value from literature is used. In the current state, the simplified model supports a linear unclipping motion and therefore no transverse forces can be applied, which might have an impact on the actual holding force. With the intended compromise between accuracy and modelling effort in mind, the simulation is assumed to be sufficient since the analysis of the transferability of the RD principles were primary focused, which could be effectively shown with the results.

7 Conclusion and Outlook

The EFRT-Model provides a suitable thinking tool for analysing RD principles, as it matches the information content in early stages of product development with the graphical approach based on concept sketches. The creation of the EFRT-Sketch and -Graph required only a few minutes and the analysis approximately two hours in a group discussion. The effort required to create the model is therefore manageable compared to extensive simulations, which took several hours plus efforts for the verification of the simulation model, especially when iterations occur and adaptions need to be made to the concept. This was demonstrated using the example of the snap fit joint design, as changing the configuration even leads to a change in the concept for retaining the latching hook. Within this contribution, the following research questions was raised: *Which RD principles for concept analysis can be transferred to an early robust embodiment design utilising the EFRT-model?* This question can be answered as follows: The transferability of a total of nine RD principles were assessed on a four-point scale in the context of the snap fit joint design use case. For *design clarity of contacts* and *elasticity*, the utilisation was high, since the use cases uses elasticity within the product function and clarity about contacts is needed. *Load paths*, *number of design parameters* and *self-reinforcement* had a utilisation assessment of middle, because trade-offs regarding functionality or dependency to other RD principles were noticeable, as shown in Table 1. This applies for the RD principles with a low assessment as well, which are *uncoupling* and *adding-tolerance adjustment*. Two of the nine RD principles were not utilisable, namely *shielding from the cause of variation* and *system mobility*. The transferability to the simulation perspective was analysed with a special focus on creating the simulation model as well as the simulation results. By that, two main conclusions could be drawn from the theoretical perspective. They include the focus on ensuring clear contacts through spaces for variation compensation and the necessary trade-off between functional fulfilment and suggestions derived from the RD principles. The latter is for example utilisable in context of the defined KCs in the clipped in state, which cannot be minimised simultaneously.

For future research in the field of RD, more experiments need to be conducted in order to derive and validate robustness considerations (Eifler and Schleich, 2021). In the context of the snap fit joint design use case, this could be tackled by a more detailed simulation model of the joint and an empirical study on manufactured snap fit joints. This implies an analysis on each variation that is induced by manufacturing, measurement and testing. Regarding the theoretical perspective, future research in the context of RD in early stages of product development could focus approaches that ease the use of simulation tools. With the two-dimensional simulation model in mind, this could be achieved by automated sketch detection with artificial intelligence in order to accelerate the transition from sketches to an initial simulation model.

Acknowledgments

The authors thank the German Research Foundation (DFG) for supporting the project ‘Holistic robustness evaluation in early design stages’ under grant numbers WA 2913/52-1 and MA 5940/23-1.

References

Aira, J.R., Arriaga, F., Íñiguez-González, G., Crespo, J., 2014. Static and kinetic friction coefficients of Scots pine (Pinus sylvestris L.), parallel and perpendicular to grain direction. Materiales de Construcción 64, e030. https://doi.org/10.3989/mc.2014.03913.

Armillotta, A., 2015. Force analysis as a support to computer-aided tolerancing of planar linkages. Mechanism and Machine Theory 93, 11–25. https://doi.org/10.1016/j.mechmachtheory.2015.06.015.

Bayer Material Science, 2013. Snap-fit joints for plastics - a design guide. Bayer Material Science LLC, Pittsburg, USA, 26 pp.

Eifler, T., Campean, F., Husung, S., Schleich, B., 2023. Perspectives on Robust Design – an Overview of Challenges and Research Areas Across Industry Fields. Proceedings of the Design Society 3, 2885–2894. https://doi.org/10.1017/pds.2023.289.

Eifler, T., Christensen, M.E., Howard, T.J., 2013. A classification of the industrial relevance of robust design methods, in: Proceedings of the 19th International Conference on Engineering Design (ICED13): Design For Harmonies (Vol. 9), Seoul, Korea. 19-22.08.2013. Design Society, pp. 427–436.

Eifler, T., Schleich, B., 2021. A Robust Design Research Landscape - Review on the Importance of Design Research for Achieving Product Robustness. Proceedings of the Design Society 1, 211–220. https://doi.org/10.1017/pds.2021.22.

Fazl Mashhadi, A., Alänge, S., Gustafsson, G., Roos, L.-U., 2016. The Volvo Robust Engineering System: how to make robust design work in an industrial context. Total Quality Management & Business Excellence 27, 647–665. https://doi.org/10.1080/14783363.2015.1039938.

Fazl Mashhadi, A., Alänge, S., Roos, L.-U., 2012. Introducing robust design in product development: Learning from an initiative at Volvo. Total Quality Management & Business Excellence 23, 1191–1205. https://doi.org/10.1080/14783363.2012.728847.

Goetz, S., Hartung, J., Schleich, B., Wartzack, S., 2019. Robustness Evaluation of Product Concepts based on Function Structures, in: Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft, Netherlands. 05.-08.08.2019. Cambridge University Press, pp. 3521–3530.

Goetz, S., Roth, M., Schleich, B., 2021. Early Robust Design—Its Effect on Parameter and Tolerance Optimization. Applied Sciences 11, 9407. https://doi.org/10.3390/app11209407.

Goetz, S., Schleich, B., Wartzack, S., 2020. Integration of robust and tolerance design in early stages of the product development process. Research in Engineering Design 31, 157–173. https://doi.org/10.1007/s00163-019-00328-2.

Grauberger, P., Goetz, S., Schleich, B., Gwosch, T., Matthiesen, S., Wartzack, S., 2020a. A Conceptual Model Combination for the Unification of Design and Tolerancing in Robust Design, in: Proceedings of the 16th International Design Conference (DESIGN2020). DESIGN2020, Online-Conference. 26.-29.10.2020. Cambridge University Press, pp. 157–166.

Grauberger, P., Wessels, H., Gladysz, B., Bursac, N., Matthiesen, S., Albers, A., 2020b. The contact and channel approach – 20 years of application experience in product engineering. Journal of Engineering Design 31, 241–265. https://doi.org/10.1080/09544828.2019.1699035.

Hasenkamp, T., Arvidsson, M., Gremyr, I., 2009. A review of practices for robust design methodology. Journal of Engineering Design 20, 645–657. https://doi.org/10.1080/09544820802275557.

Horber, D., Li, J., Grauberger, P., Schleich, B., Matthiesen, S., Wartzack, S., 2022. A model-based approach for early robustness evaluation - Combination of Contact and Channel Approach with tolerance graphs in SysML, in: Proceedings of the 33rd Symposium Design for X. (DFX2022), Hamburg, Germany. 22.-23.09.2022. The Design Society, pp. 1–10.

Klahn, C., Singer, D., Meboldt, M., 2016. Design Guidelines for Additive Manufactured Snap-Fit Joints. Procedia CIRP, 264–269. https://doi.org/10.3929/ETHZ-B-000117207.

Krogstie, L., Ebro, M., Howard, T.J., 2015. How to implement and apply robust design: insights from industrial practice. Total Quality Management & Business Excellence 26, 1387–1405. https://doi.org/10.1080/14783363.2014.934520.

Li, J., Horber, D., Keller, C., Grauberger, P., Goetz, S., Wartzack, S., Matthiesen, S., 2023. Utilizing the Embodiment Function Relation and Tolerance Model for Robust Concept Design. Proceedings of the Design Society 3, 3771–3780. https://doi.org/10.1017/pds.2023.378.

Liewerenz, O., Grauberger, P., Nelius, T., Matthiesen, S., 2023. Identifying Successful Approaches During Testing Activities in Engineering Design. Proceedings of the Design Society 3, 2205–2214. https://doi.org/10.1017/pds.2023.221.

Meboldt, M., Matthiesen, S., Lohmeyer, Q., 2012. The Dilemma of Managing Iterations in Time-to-market Development Processes, in: Proceedings of the 2nd International Workshop on Modelling and Management Engineering Processes, Cambridge, United Kingdom. 29-30.11.2012, pp. 127–140.

Park, G.-J., Lee, T.-H., Lee, K.H., Hwang, K.-H., 2006. Robust Design: An Overview. AIAA Journal 44, 181–191. https://doi.org/10.2514/1.13639.

Pedersen, S.N., Christensen, M.E., Howard, T.J., 2016. Robust design requirements specification: a quantitative method for requirements development using quality loss functions. Journal of Engineering Design 27, 544–567. https://doi.org/10.1080/09544828.2016.1183163.

Sharma, G., Allen, J.K., Mistree, F., 2021. A method for robust design in a coupled decision environment. Design Science 7. https://doi.org/10.1017/dsj.2021.22.

Sols, A., 2015. Validation of the robustness of the selection of the preferred design concept through a comprehensive sensitivity analysis, in: 2015 Annual IEEE Systems Conference (SysCon) Proceedings. 2015 9th Annual IEEE International Systems Conference (SysCon), Vancouver, BC, Canada. 13.04.2015 - 16.04.2015. IEEE, pp. 403–408.

Suh, N.P., 1998. Axiomatic Design Theory for Systems. Research in Engineering Design 10, 189–209. https://doi.org/10.1007/s001639870001.

Taguchi, G., Yano, H., Chowdhury, S., Taguchi, S., 2005. Taguchi's quality engineering handbook. John Wiley & Sons, Hoboken, N.J, Livonia, Mich, 1662 pp.

Thornton, A.C., 1999. A Mathematical Framework for the Key Characteristic Process. Research in Engineering Design 11, 145–157. https://doi.org/10.1007/s001630050011.

Wynn, D.C., Eckert, C.M., 2017. Perspectives on iteration in design and development. Research in Engineering Design 28, 153–184. https://doi.org/10.1007/s00163-016-0226-3.

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