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A CONCEPTUAL MODEL COMBINATION FOR THE UNIFICATION OF DESIGN AND TOLERANCING IN ROBUST DESIGN

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Abstract

In design engineering, the early consideration of tolerance chains contributes to robust design. For this, a link of design and tolerancing domains is essential. This paper presents a combination of the graph-based tolerancing approach and the Contact and Channel approach to link these domains. The combined approach is applied at a coinage machine. Here it provides detailed insights into state-dependent relations of embodiment and functions, which can improve robustness evaluation of the concept. This approach shows a possibility to bridge the gap between design and tolerancing domains.

Keywords: *engineering design, modelling, tolerance representation and management, robust design*

1. Introduction

In the last decades, increasing product complexity and the striving for shorter development times led to an increasing challenge to meet the high customers' requirements (Thornton, 2004). This inevitably led to a virtual product development in order to ensure the products quality in the early design stages according to the first-time-right principle (Bordegoni and Rizzi, 2011). The virtual product development relies heavily on built up models of the product. These models reduce complex relations to essential issues and thus enable managing them (Stachowiak, 1973). Depending on the availability of product information and the modelling level, various models with different degrees of abstraction are built up in product development (Ehrlenspiel and Meerkamm, 2017). This correlates in particular with the progressive product specification along the stages of the product development process, exemplarily defined by Pahl and Beitz (2007). In addition to this, the extent and content of simultaneously used models significantly differs depending on the domain in which they are applied (Baysal and Roy, 2014).

A challenge in model building in design engineering is modelling relations of the products embodiment and its behaviour or functions, as these are two different domains (Matthiesen, 2011).

1.1. The design domain - modelling embodiment and functions

Many models enable depiction of these embodiment function relations (EFRs) with different focus (Matthiesen, 2019a). Qualitative modelling of EFRs is used as support to create quantitative models such as models based on finite element method (FEM), multibody simulations, etc. in a targeted way (Matthiesen et al., 2018). The sketch-based 'organ domain models' support in ideation (Andreasen et al., 2015). Based on freely selectable visualisations of technical systems, the Contact and Channel Approach

(C&C²-Approach) supports design engineers as thinking tool for EFRs (Matthiesen, 2002; Albers and Wintergerst, 2014). This approach is described in more detail in section 2.1. Axiomatic Design (Suh, 1998) supports optimization based on functional integration. For structuring of EFRs, the Characteristics Properties Modelling (CPM) by Weber (2014) can be used. Concluding, design oriented modelling approaches mostly aim at defining the products embodiment including structure and parameters, but do not consider variation of these parameters that occur through various causes (e.g. scatter from manufacturing).

1.2. The tolerancing domain - modelling the details of embodiment

In the domain of tolerancing activities, understanding the EFRs is particularly relevant, since tolerancing aims to ensure a proper functionality of products by enhancing the robustness and defining appropriate tolerances. With regard to consistency and traceability, this requires a close linkage of tolerances with embodiment and function definition (Srinivasan et al., 1996; Schleich et al., 2018), for example in a common product model (Jérome and Denis, 2008). Thus, there are already some approaches in the tolerancing domain that focus on linking geometry specification and function. Some approaches propose a function-oriented tolerance specification (Hu and Peng, 2011) and analysis (Ledoux and Teissandier, 2013), without specifically addressing the link to functions. On the contrary, CPM is used for the identification of uncertainties as basis for the subsequent tolerancing (Malmiry et al., 2016). Finally, the matrix for the comparison of the functional requirements and the design parameters including tolerances presented by Islam (2004) can contribute to an improved system understanding and thus to a targeted functional tolerancing. In summary, it can be stated that the existing tolerance modelling approaches either only meagrely deal with the linkage of embodiment and function or require a nearly fully defined geometry. Although a function-oriented tolerance consideration is sought, a straight link to the EFRs is missing in conceptual design due to the lack of detailed product information.

Thus, these tolerancing approaches are primarily limited to the later stages of product development with the associated robust parameter design and tolerance modelling, where quantitative computer-aided models are usually already available (Davidson, 2007). They aim at defining tolerance chains for the already defined products in order to ensure the functionality of the manufactured product. However, in the context of a tolerance-driven product development, this has only comparatively small influence (Jugulum and Frey, 2007). Rather, a robust concept design according to Taguchi contributes to the robustness and performance of a product (Taguchi et al., 2004). Nevertheless, most existing approaches from the tolerance domain are not applicable in the conceptual design stage due to the lack of detailed product information. This leads to alternative models that represent the relationships of a product concept in a structured way and thus allow a link to other domains (Dantan et al., 2003). In the tolerance domain, graphs that represent the little information available in the conceptual design and can be continuously extended along the ongoing product development are frequently used (Ballu and Mathieu, 1999). An approach for graph-based tolerancing in the concept design stage is described in detail in section 2.2.

In conclusion, it can be stated that despite the great importance of the product concept for robust design and the indisputable benefit of linking tolerance and design domain, there is currently no sufficient link usable in the conceptual design stage. Thus, with regard to the linkage of different models aimed at in holistic product development (Walden et al., 2015; Walter et al., 2015), the following research question can be derived:

To what extent can an enhanced evaluation of the product concept robustness be achieved by combining the graph-based tolerance and robustness evaluation approach with the C&C²-Approach?

2. Preliminaries

In the following, a short overview is given of the approaches that are combined in this paper to investigate the research question.

2.1. The C&C²-Approach - modelling qualitative embodiment function relations

This section is based on Matthiesen et al. (2019b). Parts of the following text are taken from that paper without changes. With the C&C²-Approach, qualitative system understanding can be built up. It

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supports design engineers in thinking in EFRs and allows modelling of states and elements relevant for fulfilling the systems functions. It contains three key elements and three basic hypotheses that define the usage of its key elements. An overview of the three key elements Working Surface Pair (WSP), Channel and Support Structure (CSS) and Connector (C) is depicted in Figure 1.

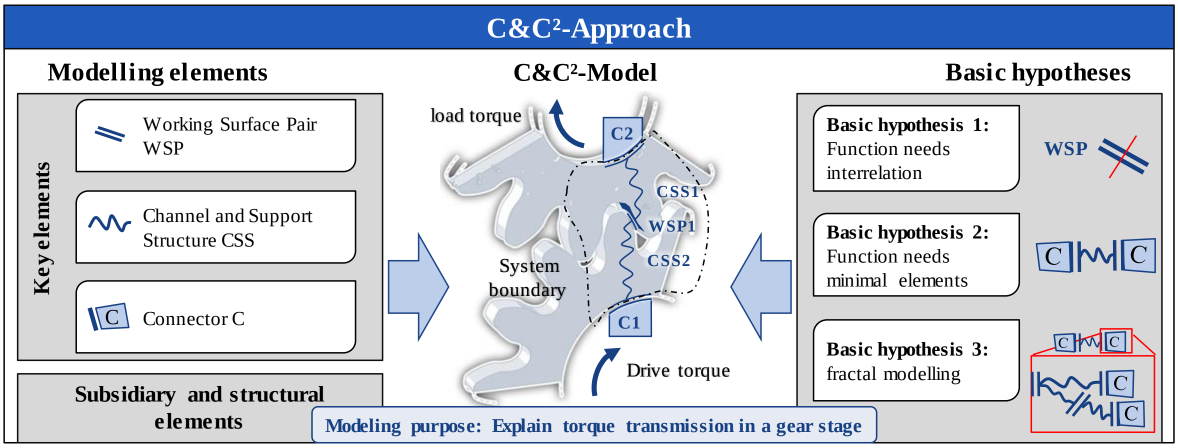

Figure 1. Overview of the C&C²-Approach and its elements (Matthiesen et al., 2018)

A WSP describes the interface where parts of the system connect while it fulfils its function. The CSS goes through system parts and connects the WSP. A CSS can include parts of components or whole subsystems depending to the modelling purpose. The Cs represent the system boundary and contain function-relevant effects of the environment on the system (Albers and Wintergerst, 2014). These key elements are depicted in Figure 1 on the left side. They contain parameters of the embodiment that are relevant for the function fulfilment. The basic hypotheses describe possibilities and boundaries of the modelling with the C&C²-Approach. They are depicted in Figure 1 (right side).

By applying the key elements and basic hypotheses to a systems visualisation, a C&C²-Model is created (Figure 1, centre) (Matthiesen et al., 2019b).

When a system changes its states during function fulfilment, state-dependent EFRs can be modelled by combining different C&C²-Models in the structure of the C&C²-Sequence model. This enables a structure of EFRs and supports in analysis of complicated technical systems (Matthiesen et al., 2019b). With the C&C²-Sequence model, qualitative analyses of quasi-static and dynamic EFRs can be conducted based on the static C&C²-Models.

2.2. Graph-based tolerancing approach - considering tolerances in conceptual design

The graph-based tolerancing approach is a method and a tool enabling the consideration of variation in the conceptual design stage. It uses the fact that the relevant geometry elements in the contact areas that are decisive for tolerancing and robustness are implicitly available in the conceptual design stage (Ballu et al., 2006). The resulting graphs of the procedure shown in Figure 2 represent the structure of the relevant geometry elements including a qualitative tolerance specification. This tolerance structure graph enables a robustness evaluation of the product structure usually defined at the end of the conceptual design stage (Goetz et al., 2018).

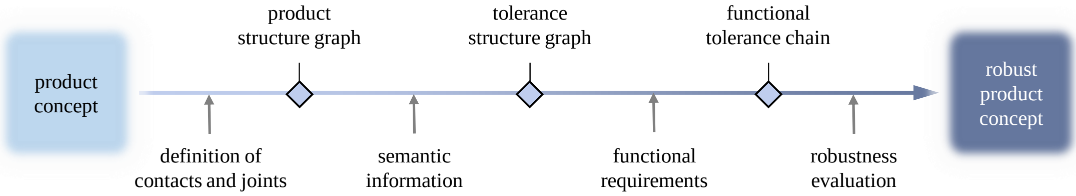

Figure 2. Process of graph-based tolerancing and robustness evaluation according to Goetz et al. (2018)

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In the first step of the process shown in Figure 2, the product concept exemplarily represented by a diagrammatic sketch is translated to a product structure graph. By adding the definition of contacts and joints, this graph represents relevant product components and the connection types of adjacent components. Since the components and the connection types already imply essential geometric elements as well as their spatial arrangement, a semantic database is used for the automated transfer to the tolerance structure graph. Although the majority of geometric tolerances is generated automatically in this structure, the designer has the opportunity to add further tolerances at this stage of the process. In combination with the functional requirements, including the corresponding functional key characteristics previously defined in the product development process, the tolerance chains in the form of loops in the graph can be derived from the structured tolerance concept (see also Figure 4, centre). The resulting functional tolerance chains, which are the last milestone in the tolerancing approach, help to compare the robustness of different concepts or product structures with respect to the Axiomatic Design (Suh, 1998) and thus to select the most robust concept. (Goetz et al., 2018)
Moreover, the resulting tolerance chains for each functional key characteristic indicate some design changes that further improve the conceptual robustness. In addition, the tolerance structure provides useful information for the further design and tolerancing process with regard to the robustness and tolerances of a product. This allows a more detailed examination of the robustness of a product than usually possible at the end of the concept design stage. Thus, it bridges the gap between the sparse product information in concept design and the concrete geometry definition in the embodiment design.

3. Methodical approach and case study

To address the research question, a modelling study is conducted based on an existing project where the graph-based tolerancing approach was implemented. It is evaluated whether uncovered challenges can be resolved by the developed enhanced modelling approach that is based on the combination of the graph-based tolerancing approach and the C&C²-Approach.
The combined approach is developed by identifying easy-to-establish links between the graph-based tolerancing approach and the C&C²-Approach. This combined approach is called the *Embodiment-function-driven tolerancing* and is first described in short in section 3.1. Then the case study and the corresponding initial tolerance graph are outlined in section 3.2. In section 4, the *Embodiment-function-driven tolerancing* is applied to the case study and the results are discussed in section 5.

3.1. Embodiment-function-driven tolerancing - the combined approach

The derivation of the combined approach *Embodiment-function-driven tolerancing* from the graph-based tolerancing approach and the C&C²-Approach is shown in Figure 3.

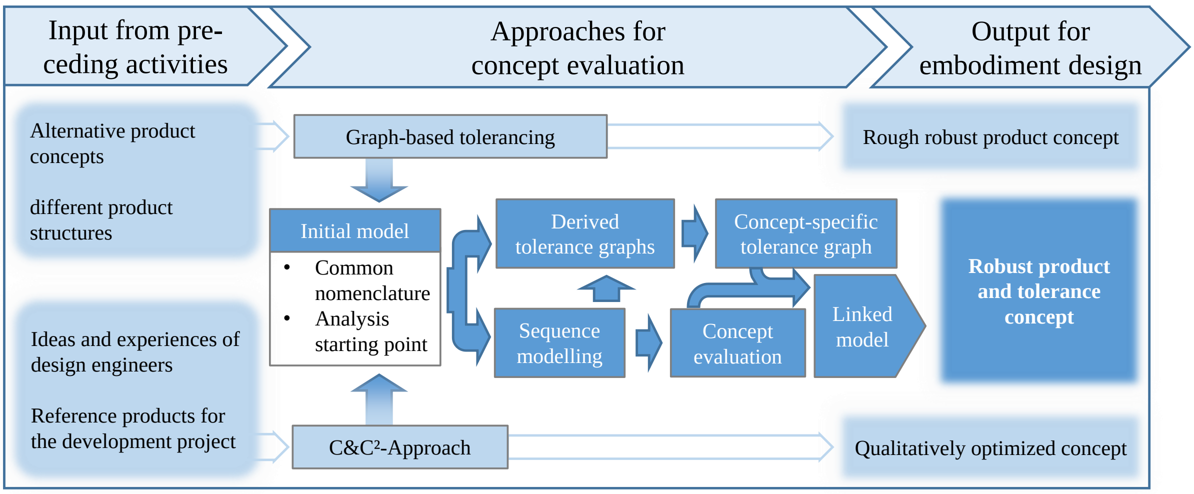

Figure 3. Embodiment-function-driven tolerancing - combination of graph-based tolerancing and C&C²-Approach

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Here on the left, the input for the graph-based tolerancing and the C&C²-Approach are shown. The graph-based tolerancing needs alternative product concepts or different product structures as input for the robustness evaluation. The output is a rough robust concept including tolerance chains. The C&C²-Approach needs ideas and experiences of design engineers about how the system in development might work. It often also uses reference products like the preceding product or competitor products. With this input, qualitative insights about EFRs are possible, leading to qualitatively optimized concepts.

The combined approach first needs an overview of the systems tolerance graph for nomenclature. This also can be used as starting point for building up the C&C²-Model. Based on this, locations of function fulfilment are identified in the built up C&C²-Model. In the locations of function fulfilment, a C&C²-Sequence model is created to identify state-dependent EFRs. Depending on the identified states, different tolerance graphs can be derived, as tolerance chains become also visible in the C&C²-Models e.g. through the flow of forces. In critical states, an in-depth analysis is conducted and more detailed C&C²-Models are created. These models are then linked back to the tolerance graph of the critical state. This leads to a documentation of the relation of tolerances and system behaviour that can be used in later embodiment design to investigate why a certain tolerance was chosen. The procedure of the combined approach is explained in detail in the application at the coinage machine in section 4.

3.2. Tolerance graph analysis of a coinage machine as starting point

In order to test the initial model combination, the *Embodiment-function-driven tolerancing* is applied to a coinage machine. The key element of the hand-operated coinage machine is a toggle lever mechanism that presses the punch onto the blank with the force required for minting. The basic concept is shown in Figure 4 on the left. In order to ensure a high minting quality, the tilting α of the stamping surface is initially defined as a functional key characteristic.

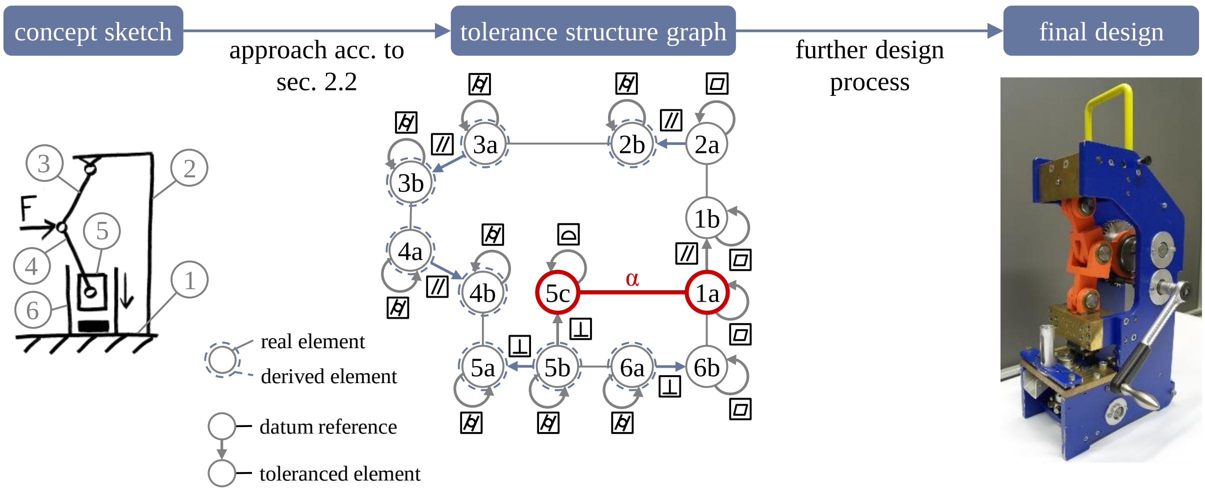

Figure 4. Generation of tolerance structure graph for coinage machine according to Goetz et al. (2018)

The application of the graph-based procedure described in section 2.2 to the concept sketch results in the tolerance graph shown in the centre of Figure 4. In addition to the geometry element nodes and the geometric tolerances, the tilting angle α between the two determining surfaces is shown in the graph. This representation reveals that the functional key characteristic is determined by two tolerance loops indicating a potential overdeterminacy. In the sense of improved robustness, this can be eliminated in the further development process, for example by inserting large clearance or compliant elements in the long tolerance chain. This proposed design adaptation decouples the tolerance chains, so that the tilting now only depends on the small tolerance loop, which should be considered in detail during further product development. This is where the existing graph-based approach links up with the established processes of further product and tolerance design. The subsequent steps of the product development process lead to the final design, which is shown on the right in Figure 4. Some additional

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components such as gear wheels and eccentrics for the transmission of a rotary hand movement into a translatory force application with the corresponding geometry elements are added. Even though these elements are not considered in the tolerance structure graph, the robustness evaluation is reliable, since they only affect the force application and are therefore completely decoupled from the guiding or tilting of the punch. However, the robustness evaluation is currently limited to a pure graph analysis with regard to the Axiomatic Design without going into detail on the geometry elements in contact or changing states over time.

4. Application of the embodiment-function-driven tolerancing - investigating system states and robustness of concepts

Since the *Embodiment-function-driven tolerancing* aims at overcoming the current limitations of the graph-based tolerancing and C&C²-Approach, it is applied to the coinage machine described in section 3.1. First, two overview-models of the coinage machine are modelled in the graph-based tolerancing and C&C²-Approach, which form the basis for further investigation. They are displayed in Figure 5. Here, besides the nomenclature, another similarity can be observed, as both models are able to describe connections between components enabling a consistent denotation of the elements.

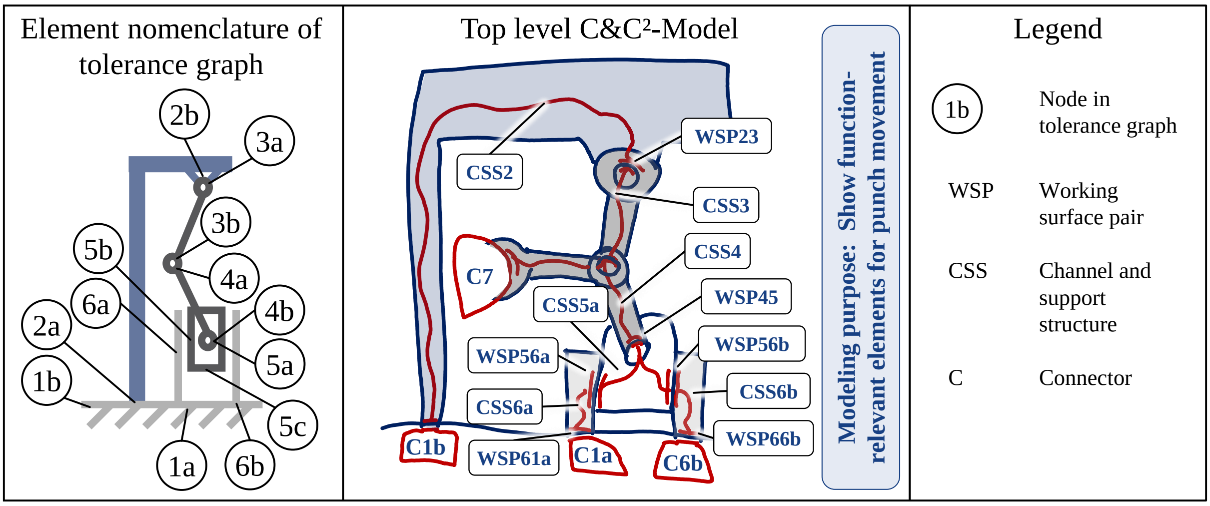

Figure 5. Top level models of the tolerance graph and C&C²-Approach

The sketch on the left in Figure 5 is the basis for the creation of the tolerance structure graph and presents the labels of the relevant geometry elements, which are used in the graph. Similar numbers are given to the elements of the C&C²-Approach used to model the top level C&C²-Model (Figure 5, centre). The tolerance graph uses a schematic visualisation, while the C&C²-Model is based on a freehand sketch, as it might be created in a creative session. Here, the starting points for detailed modelling of EFRs are defined. In this way, a detailed investigation of the main function "coin minting" takes place, which is depicted in Figure 6. Here, based on the overview model, the states of the system are modelled in a C&C²-Sequence Model.

In the C&C²-Sequence Model, five hypothetical states of the machine concept are identified. However for the function "coin minting" only the states 2 (drive rotation angle 270°), 3 (360°) and 4 (450°) are assumed as relevant, as a WSP exists between stamp and coin. Thus, the modelling is limited to these states. In state 2, the stamp comes into contact with the coin. Here it can be seen that clearance is necessary for movement of the punch. Due to the angular force introduction, the lateral **WSPs 56a** and **56b** are formed, where fit, size of the WSPs and hardness difference are assumed as important. These WSPs also determine the angular error α that leads to a faulty **WSP 56c**. This angle becomes function-relevant in state 3, where it determines the quality of minting.

In state 3, the maximum force is applied. In **C 45** the maximum force is applied, leading to dissolving of the **WSP 56a**, as even if still contact exists, it is no longer relevant for the function because the

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force is almost completely supported by the coin, and the punch is guided by **WSP 56b**. In state 4, the force direction changes in connector **C45**. The **WSP 56a** comes into contact again.

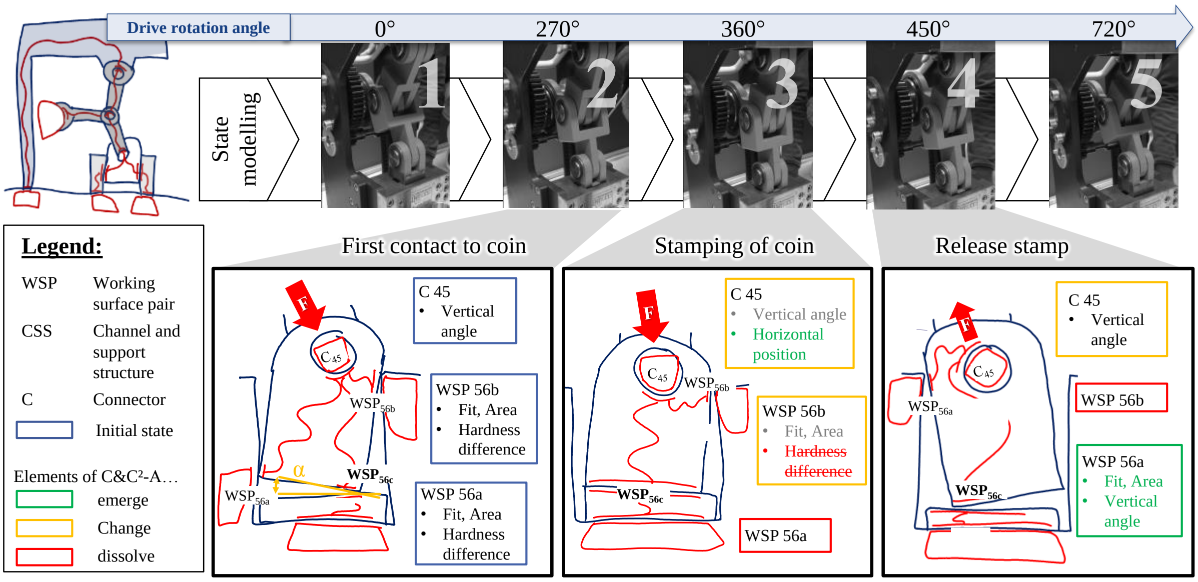

Figure 6. C&C²-Sequence model of the coinage machine

As can be seen, in the three different states, various WSPs are relevant for the function "coin minting". This results in different tolerance chains for each state, which must be considered simultaneously for a complete consideration of the function. In contrast to the former procedure, the C&C²-Sequence model contributes directly to deriving the various relevant tolerance graphs and thus to an improved understanding of the function-relevant tolerances in critical system states. Moreover, this model allows an in-depth investigation of the influence of the lateral WSPs on the function-relevant angle α.

In a zoom-in into state 2 (see Figure 7), it can be seen that the horizontal angle α depends on the fit in WSP 56a and WSP 56b. The hardness difference (punch is harder than guidance) might make the WSP 56b vulnerable for wear and increased play in the fit until the edge is round and surface tension decreases. In the WSP 56a, the harder edge of the piston might clear away the guidance without losing its sharpness. Here, the critical wear is identified, as no decrease of the surface tension in the WSP occurs over time. A concept optimization can take place, e.g. integrate radii at the WSPs (Figure 7, right). Other possibilities which can improve the reliability of the system can be guidance by roller bearings or external guidance.

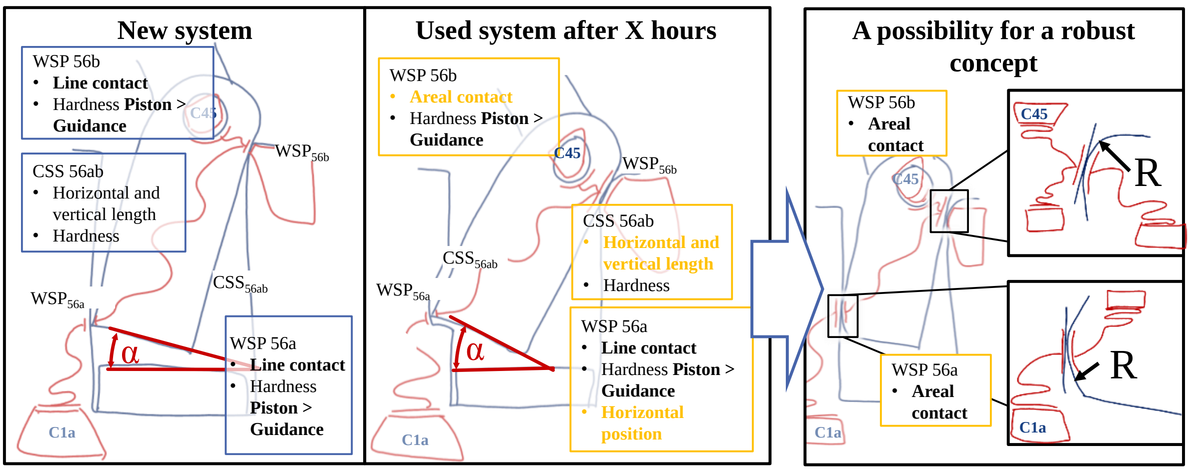

Figure 7. Concept improvement

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The gathered information about the contact between punch and guidance from the detailed analysis with the C&C²-Approach is then fed back into the tolerance graphs, see Figure 8.

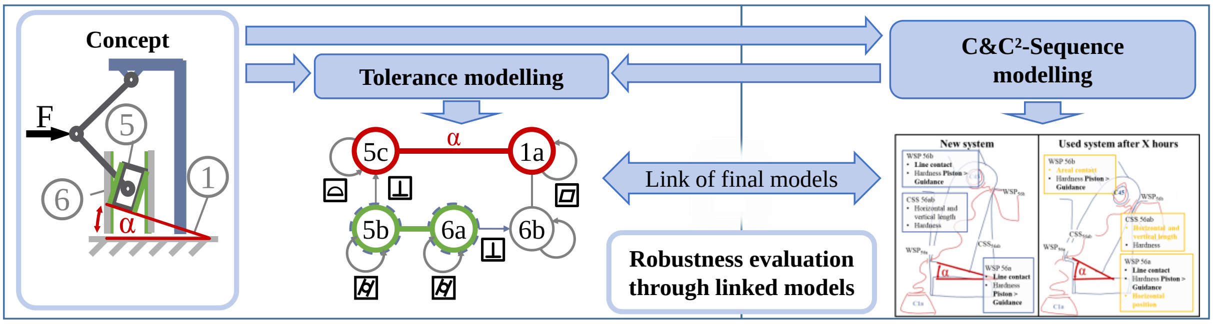

Figure 8. Enhanced tolerance structure graph of the relevant loop for the functional key characteristic α with link to C&C²-Model of detailed EFRs

In this way, the fit with necessary clearance between punch and guidance with the corresponding surfaces 5b and 6a (respectively WSP 56a and 56b) is highlighted in green in the tolerance loop graph. Moreover, a link (in the current implementation URL based) is added to this coloured edge connecting the tolerance graph to the C&C²-Model. Based on the linked models, an enhanced robustness evaluation is now possible, as causes for chosen tolerances can be traced back into the C&C²-Models.

5. Discussion

The combination of the models in the *Embodiment-function-driven tolerancing* shows synergy potential regarding the strengths of the models without losing major advantages of the two separate models. The combination of the models is facilitated through the similar nomenclature that enables a common basis for modelling. The fractal character of the C&C²-Approach is used for lean modelling of function-relevant embodiment parameters and the resulting models can be linked to the tolerance graph. The state-dependent analysis enables the derivation of specific tolerance graphs. Instead of evaluating the robustness of the concept as common for all operating states, the individual states in which the structure relevant for the robustness evaluation changes significantly can now be analysed separately with a specific tolerance graph. The link of the tolerance graph and the detailed C&C²-Models enables modelling of EFRs and tolerances in a joint environment. The graph-based tolerancing enables the transition of qualitative knowledge about EFRs from the C&C²-Approach into quantitative models.

Based on this, the research question can be answered in the way that the robustness evaluation with the graph-based tolerancing approach can be enhanced through the consideration of system states and fractal modelling of details of the system. The *Embodiment-function-driven tolerancing* can support the further steps in the product development process and thus pushes the transition to embodiment design e.g. with regard to system reliability. Thus, the new approach facilitates the vector based tolerance analysis modelling representing the product behaviour under variation and therefore enables an early quantitative validation. Depending on the progress of the product development process, a definition of the essential product dimensions, which are usually only defined in the embodiment design stage, is necessary. The combined approach, however, already allows the modelling of the contact surfaces to be derived and the vectorial sequence of these surfaces specified by the tolerance loop to be realized.

Although the combination of the two approaches enables a detailed and thus more reliable robustness evaluation, a current limitation is the necessity of manual transfer of the information from the sketch-based C&C²-Models into the tolerance graphs. The links between the models have up to now been developed by a pragmatic approach and need further research, for example into how the linked models are structured when more than one function is considered. This could mean many different C&C²-Models linked to one tolerance graph. For investigating success criteria of the *Embodiment-function-driven tolerancing* like usefulness or applicability, the application in a project without previous applications of the separate approaches is necessary. To gain quantitative statements about advantages of improvements regarding time and costs, follow-up studies are necessary. A more general limitation is the focus on mechanical system parts, where the focus of the underlying models lies.

6. Conclusion and outlook

This research project investigates, whether the combination of models for tolerance analysis and qualitative embodiment function relations creates added value in terms of the information required for robust concept evaluation. It started from the challenge that the link of design and tolerancing domain is still difficult in conceptual design. A reflection on models applicable in conceptual design leads to selection of modelling approaches and the following research question: *To what extent can an enhanced evaluation of the product concept robustness be achieved by combining the graph-based tolerance and robustness evaluation approach with the C&C²-Approach?*
The C&C²-Approach as qualitative design model and the graph-based tolerancing approach as tolerancing model were combined into the *Embodiment-function-driven tolerancing* for support of design engineers in conceptual design. This approach was then used in a case study of a coinage machine. Here, it was possible to enhance the robust concept evaluation by enabling investigation of state-dependent embodiment function relations and using the fractal character of the C&C²-Approach for detailed investigation. The gained knowledge was then integrated into a linked model containing the tolerance graph and the analysis with the C&C²-Approach. For a more detailed consideration and elaboration of a support by the *Embodiment-function-driven tolerancing*, it is necessary to develop the links between the models in a more detailed way. For improving it further, an investigation of its usefulness and applicability in a project without previous model-specific knowledge is necessary. Furthermore, a feedback of quantitative data from simulation is important in order to verify the models and to gain knowledge for product generation development, which is common in industrial practice.

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