A model-based approach for early robustness evaluation – Combination of Contact and Channel Approach with tolerance graphs in SysML

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Abstract

Considering variations is essential for the development of robust products, but the applicability of existing robust design approaches in early stages is challenging due to the lack of product information and high levels of abstraction. To overcome this, a combined model is presented, which enables a holistic robustness evaluation in a linked approach. This approach uses the contact and channel approach to identify the relations between embodiment and functions as well as the robustness evaluation based on tolerance graphs. The combined model is implemented with the Systems Modeling Language (SysML) and applied to a coining machine use case. An initial assessment of the model combination and a proposal for a methodically supported workflow for the holistic robustness evaluation is given.

Keywords

Robust Design, Variation Management, Contact and Channel Approach, SysML, Model-based Development

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1. Introduction and Motivation

Today's product development requires new approaches and methods that enable product developers to react to and handle the increasing requirements, for example due to the increase in product complexity. In the context of virtual product development, the first-time-right principle is therefore intended, whereby the quality of the product is already assured in early phases to avoid unnecessary and cost-intensive iterations [1]. For achieving this demanded quality in early phases, it is essential to manage the sensitivity towards variations, triggered for instance due to manufacturing or environmental conditions [2], since efforts and costs for changes increase exponentially during the development process. Variation management in particular has an important task in this context, as it has a significant influence on the later quality of the product. However, there is a major challenge, since many interactions exist in the product itself as well as in processes or even in later use, which have to be taken into account throughout the entire product life cycle [3]. Early considerations can be achieved through the development of a robust concept for the later product [4]. Robustness, which is defined as the insensitivity to variations of different sources, can be achieved through methods of Robust Design, which fundamentals originate from TAGUCHI [4].The application of robust design offers great potential for increased efficiency of the development project. However, so far only a few approaches exist that specifically support the designer in the robustness evaluation of product concepts, since the vast majority of approaches for the robustness assessment are based on quantitative models related to the detailed product geometry. Therefore, depending on the available product information and the modeling depth, individual models with different degrees of abstraction exist [5]. Especially in early phases, the necessary depth of product information is not reached and an early robustness assessment is hindered. The variety of models further complicates the efforts of a central data model, which is strived for in today's product development [6] and offers benefits such as consistency.

In order to contribute to this goal, the present paper deals with the early robustness evaluation of product concepts in a combined model. Based on a first conceptualization [7], the theoretical concept will be extended by a unified data model, which is used to link the individual and primarily graphical models of the tolerance and design domain. Within this paper, the related work is presented in section 2, followed by relevant preliminary work regarding the used approaches of the two domains (sections 3.1 and 3.2) as well as the concept for the combined robustness evaluation in section 3.3. The derived research question (section 4) leads to the method combination and the embodiment function relation and tolerance model (EFRT model) in section 5, which was implemented in a unified model using the Systems Modeling Language (SysML) in section 6. In section 7, the model combination is evaluated and discussed, whereas a summary and an outlook are provided in section 8.

2. Related Work

Robustness evaluation of product concepts focuses on the assessment of function fulfillment whilst considering variations of the system. Especially in the physical context of robustness, embodiment function relations (EFRs) are relevant, since they describe the relationship of the product´s embodiment to its behavior and functions [8]. For the analysis of EFRs various models are available [9]. Besides the sketch-based 'organ domain models' from the approach of ANDREASEN ET AL. [10], which can be used for idea generation, in addition a model from the Contact and Channel Approach (C&C²-Approach) exists, which can be used as a thinking tool for the identification of EFRs [9, 11]. Besides these graphical approaches, there are other methods for analyzing the structure and parameters of the design, which enable a conclusion about the function that should be achieved. These include Axiomatic Design by SUH [12] and Characteristics Properties Modeling by WEBER [13]. Both approaches connect the product´s embodiment and functions, but require detailed knowledge about the contained structural dependencies and the parametric description of the design. However, in early phases, in which primarily product alternatives are on a conceptual level, this information is not completely available until later development stages [14]. Moreover, the variation of parameters is not part of the respective approaches and therefore integrating the influences of variations is currently not feasible [7]. With respect to the design domain in early stages, the consideration of qualitative for a holistic robustness evaluation is challenging due to the depth of information as well as the computer processability of the mainly graphical models.

The Robust Design Approach of TAGUCHI [4] is one of the well known methods focusing robustness in product development. Although it builds on the design and tolerance domains and enables robustness assessments, its application is hindered by the large number of available principles, which formulation is contradictory in some cases. Further approaches, which consider EFR in robustness evaluation, for example the approach by BJARKLEV [15], require a minimum level of quantitative information as well as product knowledge and, for that reason, are only applicable at later stages of development. In order to perform a holistic robustness evaluation, the impact of variations of the ideal shape regarding the functional performance has to be examined. For example, variations in contact surfaces of components can contribute to changes in system behavior and the required function [16]. Many models are available to represent this detailed information for tolerancing and computer-aided workflows usually exist for tolerance simulations of products [17]. However, many approaches from the tolerance domain require quantitative information and are therefore only applicable in the later stages of the development process. There are qualitative approaches in the tolerance domain [18], which for example focus on linking geometry, function, and requirement [19]. Moreover, there are research activities exploring abstracted structures to link this information for the tolerance domain [20, 21]. Their focus is mostly on improving the traceability of tolerance decisions [22], but their applicability is hindered by the high degree of abstraction. Graph-based approaches are also available for early robustness evaluation [23], but these do not consider EFRs. Overall, there is a lack of approaches for a reliable, early robustness evaluation [24] and the corresponding potentials remain unused. As a result of the unfaced challenges resulting from qualitative and abstract models in early development, the implementation of a holistic robustness evaluation into early stages is currently not possible.

3. Preliminary Research and Approaches

Motivated by the lack of a holistic robustness evaluation in early stages and comprising the tolerance as well as design domain, GRAUBERGER ET AL. [7] proposed a conceptual model combination in order to overcome this lack. The concept is based on the graph-based tolerancing approach [25] and the C&C²-Approach [26]. Both approaches as well as the preliminary research are presented briefly in the following sections.

3.1. Contact and Channel Approach

This section is based on the description of MATTHIESEN ET AL. [26] and gives an overview about the approach. As mentioned above, the C&C²-Approach is a thinking tool to support and structure thinking during design of a product [9]. It supports designers in understanding the qualitative system by thinking in EFRs and modeling the relevant system states. The C&C²-Approach contains three basic hypotheses and three key elements: Working Surface Pair (WSP), Channel and Support Structure (CSS) and Connector (C), which are depicted in Figure 1. The basic hypotheses (Figure 1, right side) show how the model is built up by using the key elements. After applying the key elements and basic hypotheses to a system visualization, an individual C&C²-Model is created for every system state, which is derived from the C&C²-Sequence Model, and can be used to analyze EFRs (Figure 1, centre) [26].

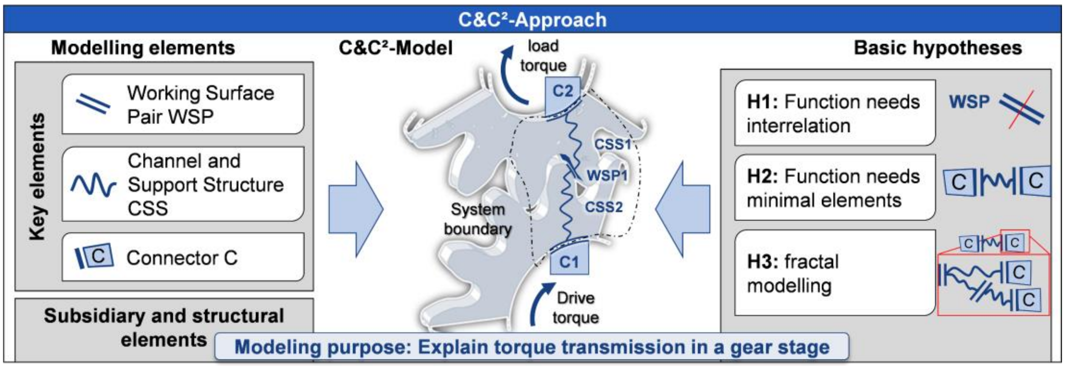

Figure 1: Overview of the C&C²-Approach and its elements according to MATTHIESEN ET AL. [26]

3.2. Graph-based tolerancing approach

In order to enable an early robustness evaluation of product concepts, GÖTZ ET AL. [25] propose a framework which uses the idea of frontloading tolerance evaluations into conceptual design. A summary of the main steps of the approach is visualized in Figure 2. It comprises the product structure graph, which is derived from the graphical product concept and is extended by geometry elements and tolerance information in order to build up the tolerance structure graph. By analyzing the function tolerance chain regarding a key characteristic, the robustness evaluation can be performed based on robust design criteria in order to compare one or more alternative concepts and to assess, which one is detailed further.

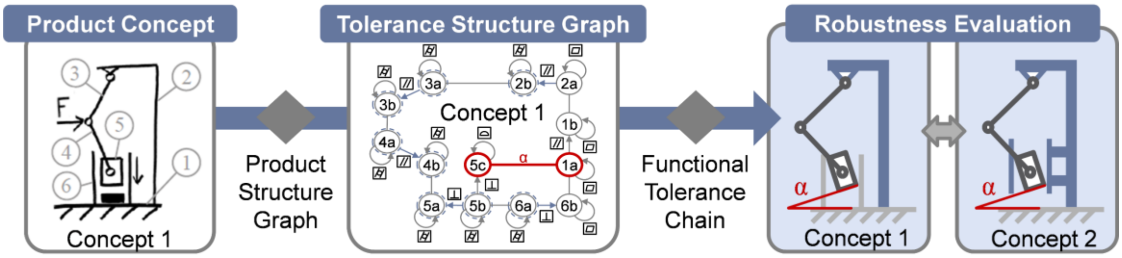

Figure 2: Robustness evaluation based on graph-based tolerancing according to GÖTZ ET AL. [25]

3.3. Conceptual Model Combination

For the intended linking of the tolerance and design domain, the C&C²-Approach for the identification of relevant embodiment information and the tolerance graph for the robustness evaluation of concepts are well suited [7]. The conceptual combination of both approaches has the advantage that an enhancement of the evaluation of robust concepts by the results of the state-dependent analysis of EFR is now possible. For this purpose, the fractal character of the C&C²-Approach was used to analyze the product concepts in the different system states identified with the C&C²-Sequence Model. The conceptual model of the linked approaches was applied to the use case of a hand-operated coinage machine, which is based on a toggle lever mechanism that presses the stamp onto the coin. The combination of both approaches as well as the product concept and its five states are shown in Figure 3. In order to assess the robustness of the product concept, the tilting of the stamping surface was identified as the relevant functional key characteristic for the quality of the coining process. In order to enable a comprehensive evaluation of the model combination in this contribution, the coining machine is also used as a use case. GRAUBERGER ET AL. [7] identify the possibility to analyze domain-specific information of both approaches, e.g. the description of properties of working surface pairs and the type of contact based on the tolerance specification, as a major advantage of the combination. The combination of the models offers high potential for robustness evaluation in early phases, but requires a common data model for further elaboration of the approach [7].

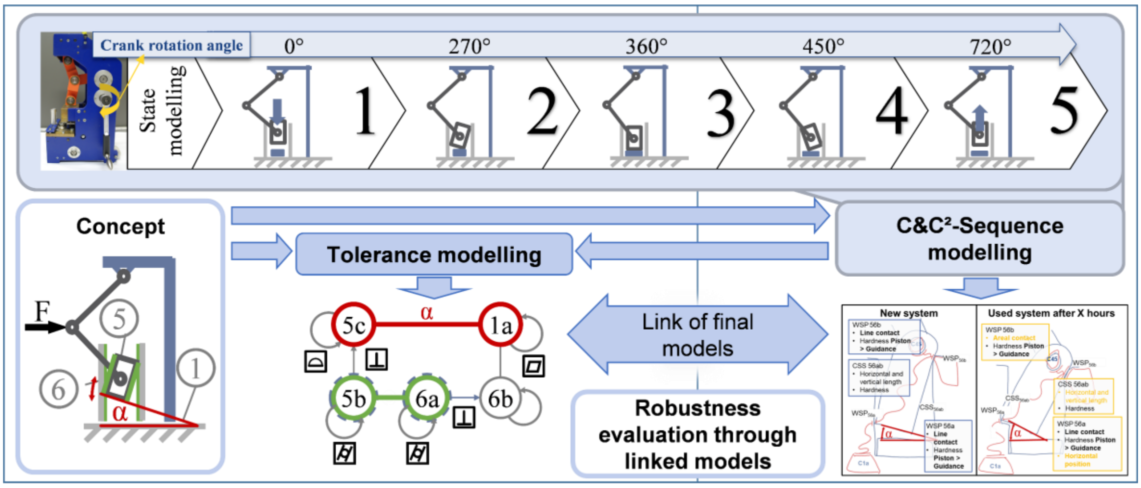

Figure 3: Graph-based tolerancing linked with C&C²-Approach and applied to a coining machine (based on [7])

4. Goal and Research Question

The state of the art in research shows that early robustness evaluation has significant importance for an efficient product development, since product concepts with little sensitivity to variations can already be identified in early development phases and thus cost-intensive iterations can be avoided. Motivated by this fact, GRAUBERGER ET AL. [7] have developed the foundations for a conceptual model linkage, which allows the combined analysis of tolerance-specific as well as product EFRs in different system states. However, due to the conceptual linkage, the approach cannot be applied effectively since a common data model is missing. For this reason, this paper answers the research question: How can the C&C²-Approach and its models be transformed into a computer-processable, common model in conjunction with the graph-based tolerancing approach? By answering this question, a contribution towards the focused goal to utilize the revealed potentials for early robustness evaluation is achieved.

5. Embodiment function relation and tolerance model (EFRT-Model)

As an essential foundation for the combined approach, this section describes the analysis of the two approaches for model linkage as well as the identified interfaces. In the present contribution, the preliminary work is extended by a combined model, which builds on their conceptual linkage regarding robustness evaluation. The result of the analysis of both approaches and the underlying link between the models is shown in Figure 4.

As a relevant approach from the tolerance domain, the graph-based tolerancing approach according to GÖTZ ET AL. [25] will now be considered in more detail. Descriptions of the models and model elements are therefore partly based on reference [25]. As shown in the upper part of Figure 4, the elements of the approach are derived from the assembly, which can be described by a set of connected parts, e.g. the coining machine (assembly) has a stamp (part) for coining. This stamp is comprised by a set of geometry elements, e.g. crown and skirt, which have individual dimensions, e.g. die skirt is based on a cylinder and therefore has a diameter and height. These basic elements are used to describe the different models in the approach. First, the product structure graph is built on the parts and their interface relations, e.g. a sliding contact between the stamp and the guide. Enhancing this graph by the semantic information regarding the geometry elements, which were defined for each part, the geometry element graph can be derived. The existing contacts can now be used to model the interaction of the geometry elements of different parts, for example the skirt of the stamp and the cylinder of the guide are connected through a sliding contact to enable the desired function. By extending the geometry element graph through tolerance specifications, the tolerance graph can be modeled and then used for the robustness evaluation regarding the key characteristics.

The analysis of the C&C^2-Approach is shown in the lower part of Figure 4 and the following description is partly based on [26]. The focus of the structure is on WSP, which can be dissolved into two working surfaces (WSs). According to hypothesis 2 in Figure 1, a function needs at least two WSPs, and these are always connected to a CSS. The design area of the system contains those WSPs and CSSs, while the Cs are modeled in the system boundary. To describe the rest of the system, residual structure (RS) and boundary surface (BS) are used, which represent the structures and surfaces that are not CSS and WS. When a system changes its states during function fulfillment, state-dependent EFRs can be modeled by combining different C&C^2-Models in the structure of the C&C^2-Sequence model. The function-relevant properties and characteristics are stored in the element itself, e.g., a WSP contains properties like friction coefficient or contact type as well as characteristics like clearance.

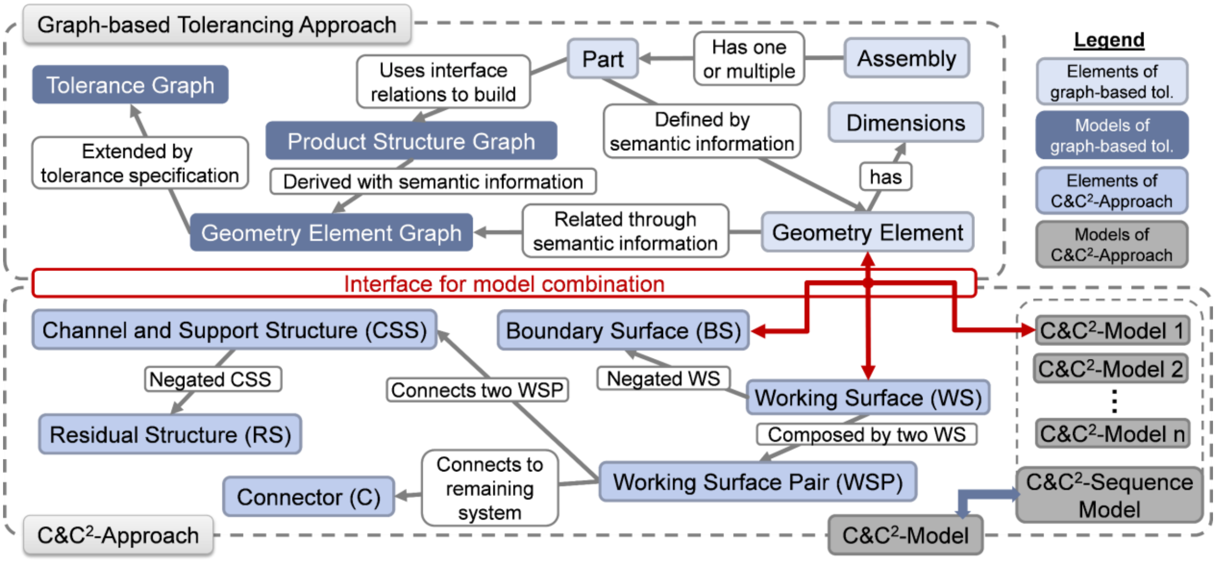

Figure 4: Analysis of graph-based tolerancing and C&C^2-Approach for identification of their model combination

The analysis of both approaches reveals that a link between them can be achieved through a surface-based interface (Figure 4, middle, red color). In the case of graph-based tolerancing, this interface connects to the geometry element, where surfaces are described and information regarding the tolerance specification are added in the tolerance graph. From the C&C^2-Approach the interface connects to BS as well as WS, where all necessary characteristics and properties are stored as stated above. As the connections to the interface in Figure 4 indicate, there is also a relevant relation to the C&C^2-Models contained in the C&C^2-Sequence Model. This is necessary, since the system can have multiple states, which are identified through the C&C^2-Sequence Model and result in an individual C&C^2-Model per analyzed state. In the different states, the relevant geometry elements and WSs as well as BSs can vary in their location, their characteristics or properties and therefore WSPs may also differ. This circumstance is investigated in Figure 5 in order to derive a modeling strategy for the common model. In the top third of Figure 5 the modeling process from the product concept (left), through sequence modeling (middle), to the tolerance graph (right) is shown. For function fulfillment, states two, three and four are relevant [7] and therefore analyzed further.

In the middle part of Figure 5 a conceptual combination of each state regarding its simplified visualization for each approach is given. It shows, that although states two and four are different in their position of the stamp and connected rods, the graph-based model with the included C&C^2-Model elements are identical. This confirms the assumption, that the interface through surface description is state dependent and might require multiple, individual surface connections. The reason for this is the two-dimensional analysis of the C&C^2-Approach. As a result, the surface-based interface and its description need a connection to the states, which is exemplarily shown for ‘state three’ in the lower third of Figure 5. The four relevant geometry elements for this state are identified and connected to their corresponding WS. For example, geometry element ‘4b’ is connected to ‘WS4b_3’, which is activated by ‘State_3’. Other states, e.g. ‘State_n’ are possible, leading to ‘WS4b_n’. For simplification reasons, other states apart from state three are not mentioned. Multiple geometry elements with their WSs build either a WSP (e.g. ‘WSP4b5a_3’) or CSS (e.g. ‘CSS5a5c_3’), but always with regard to the relevant system state. In this theoretical model, the Cs are also related to a geometry element, e.g. ‘Connector 4b’. This analysis reveals the foundations to build up the combined model, referred to as embodiment function relation and tolerance model (EFRT-model).

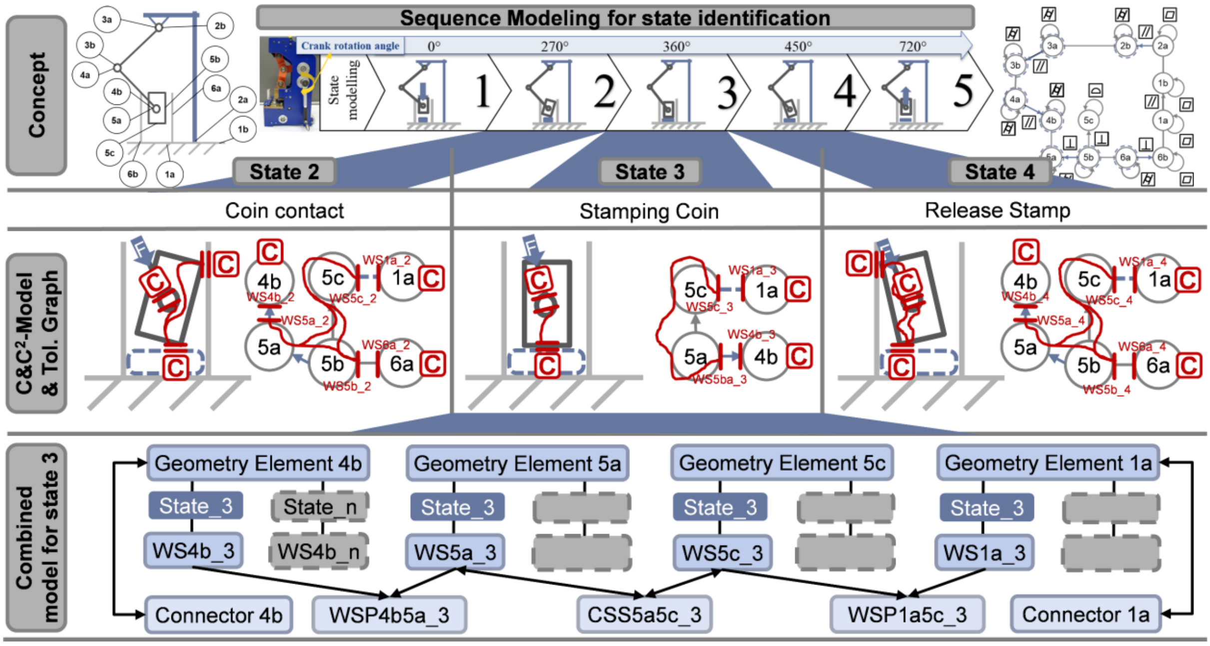

Figure 5: Foundations for the embodiment function relation and tolerance model (EFRT-model)

6. Implementation of the EFRT-Model with SysML

In order to achieve the intended goal of a common, computer-processible model (see section 4), the foundations for the EFRT-Model resulting from the previous analysis made in section 5 are implemented in a SysML-based model. The software used for the modeling purpose was Enterprise Architect, which is a commercial tool. But an implementation with an open-source software is also feasible, since no tool-specific functions are used and only extensions through specific stereotypes to the SysML-notation were done. The main reason for the use of SysML is the overlap of model elements with conventional system modeling. For example, assemblies and parts are used to represent the mechanical system. These can also be used for other modeling and development processes in the context of MBSE, which reduces the initial modeling effort. Likewise, existing models of systems can be used as a starting point and thereby be reused for the robustness evaluation, which compensates the spent effort.

The models of graph-based tolerancing, namely product, geometry element and tolerance graph are mainly modeled with block definition diagrams, where the assembly as well as all parts and geometry elements are represented as blocks and connected with relations of the type ‘connector’. Tolerance specifications as well as geometry element information are modeled as properties of the corresponding geometry element. As key characteristics are of high importance in the approach of GÖTZ ET AL. [25], they are modeled as properties and linked to the respective geometry elements. Reuse of every system element is enabled, which is important for a consistent and traceable model. Beginning with the C&C^2-Sequence Model of the C&C^2-Approach, which is modeled with state machine diagram, the relevant states can be detailed in the tolerance graph model. Since the defined design space is limited through Cs of the C&C^2-Model, which are connected to geometry elements and modeled as blocks, the remaining system can be removed. WSs are connected to geometry elements as 'ports' and connected through WSPs or CSSs (both blocks). The specification of characteristics and properties of WSs, WSPs and Cs are done through internal block diagrams and the definition of elements with the type 'property' or 'value'. Especially within the specification of WSPs, the difference between two surfaces can be modeled, e.g. the hardness difference of two WSs.

Resulting from the model interconnection, an iterative workflow is proposed that guides the steps of the combined approaches and is shown in the middle part of Figure 6. After task clarification and definition, product concepts are drawn either by hand or through digital tools. Then the product structure graph can be derived and the relevant key characteristics can be identified, which are described in the task. The graph gets extended by geometry elements and modeling of functions and system states is done afterwards, which leads to the C&C^2-Sequence Model. Now, for every included state modeled in a state machine diagram (a), an EFRT-Model (b) has to modeled. This is exemplarily shown in its implementation in SysML for the second state 'Coin contact'. In order to improve the usability of the modeling process, it is recommended to visualize the combined sketch (c) in the respective state along with the EFRT-Model. Especially in order to achieve consistency between the combined model in SysML as well as the graphical models of both approaches. The modeling of properties enables developers to specify the remaining information of the system, e.g. tolerance information, and since the EFRT-Model and tolerance graph are connected, the information is available in both. Finally, the analysis of key characteristics and robustness evaluation can be performed.

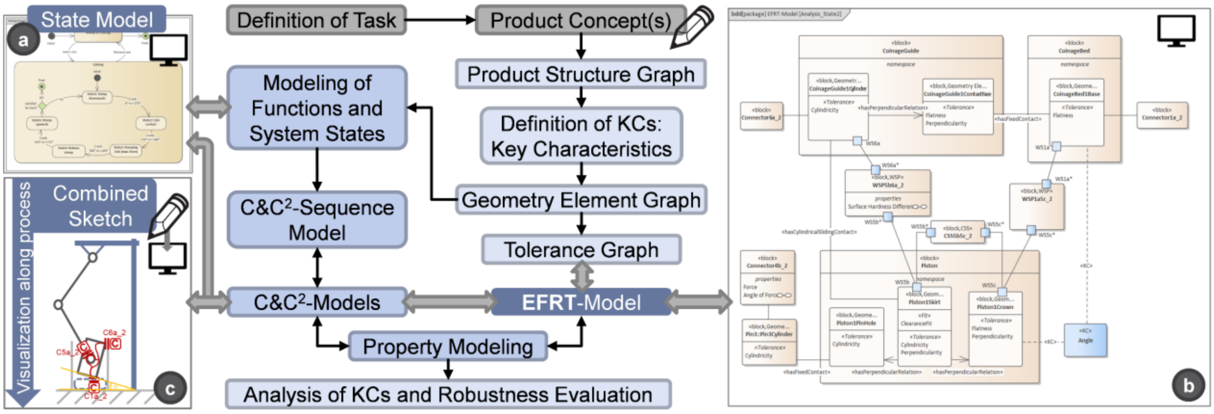

Figure 6: Proposed Workflow for the combined approach including SysML-based identification of states (a), their modeling based on the EFRT-Model (b) and the visualization of the according product concept (c)

7. Evaluation of the Model Combination and Discussion of Results

The initial evaluation of the model combination is based on the four-quadrant matrix for model modifications proposed by Fuchs [27], which uses object-based and relation-based characteristics for the assessment of model similarities and differences. The identification of the characteristics for the graph-based tolerancing and C&C^2-Approach was performed as an expert interview. In the present case, the two domain-specific, individual models are transferred into a standardized, combined model. The assessment of differences and similarities reveals, that e.g. the object characteristic 'detail' is not impacted, as all existing quantitative as well as qualitative information remain available. There is a shift in terms of the object characteristic 'representation' because of the conversion from a graphical to a system model, but there is the potential for simultaneous visualization of the sketches during modeling, e.g. in a software prototype. As Fuchs [27] states, the exchangeability and availability of information increases through the present type of model modifications. This can be confirmed, since domain-specific information can now be processed in combination, which addresses the relation characteristic 'linking direction'. In addition, there is the possibility of semi-automated transformation, for example by automated transfer of the graphs proposed by GÖTZ ET AL. [25] to SysML diagrams, which could reduce the modeling effort further.

These summarized results of the initial model evaluation show, that the combination and transformation of both models results in a gain in information that can be captured and made accessible for both domains. This leads to conclusion that the stated research question is answered through the successful model combination and the proposed workflow. But further investigations, especially through a user test are mandatory for a final evaluation. Regarding the proposed iterative workflow, an advantage to the previous approach could be achieved. For example, by the identification of critical areas in the system using C&C^2-Models alongside geometry element diagrams, since the approaches are not longer performed sequentially but are now nested within each other. However, this workflow has to be further detailed and adapted to the design task. For new product development, a different process is to be expected than for enhancement, since there is a different information and data basis. In addition, it has not yet been thoroughly resolved how robustness in the design domain can be defined in the model presented and how it can be integrated into the robustness evaluation. Furthermore, the combined approach has to be integrated into the product development process in a clear and consistent way, which according to EIFLER AND SCHLEICH [18] is rarely done in research in the field of robust design and leads to unclear necessity of approaches. They [18] also show that the use of approaches is rarely investigated, therefore the present approach of this paper has to be evaluated in the future through a user study and the benefit has to be quantified.

8. Conclusions and Future Work

Motivated by the lack of a suitable approach as well as a combined model for a holistic robustness evaluation in early phases, the present contribution answers the question on how the C&C^2 approach and its models can be transformed into a common, computer-processable model in conjunction with the graph-based tolerancing approach. For this purpose, the results of the model analysis of both approaches from the design domain as well as tolerance domain were presented, with which the foundations for the common system model were determined and combination of the models was achieved. In the holistic model, for example, function-critical areas can be identified for the first time without interfaces using tolerance graphs. That information can then be analyzed with an associated C&C^2-Model and provided to the robustness assessment. The computer processability of the model is ensured by a SysML-based approach. Besides the adaptation of the general approach to the demands of new product development or product improvement, a potential for future research remains in the investigation of the usability of the approach as well as the combined model.

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