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Design Science

Product behavior complexity metric for early prioritization of tolerance analysis tasks

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Abstract

In order to reduce the time spent on tolerance analysis, it is necessary to correctly identify and prioritize the key characteristics of the product. For multiple-state mechanisms, a systematic procedure for doing this is lacking. We present a new complexity metric for multiple-state mechanisms based on the product behavior, describing the impact of geometrical variation. The sequence of the structural state transitions is linked to the product composition, enabling a clear prioritization of variation-critical states and interfaces. The approach is applied on an industrial case and verified based on a comparison with the company-specified priority tolerance calculations.

Key words: tolerance analysis management, robust design, product behavior complexity, key characteristics identification

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1. Introduction

It is crucial for manufacturers of mechanical products to reduce the variation of the functional performance. On the one hand, it is obvious that variation of functional performance carries a risk of dissatisfied customer expectations to the point of high rates of customer complaints, damage of company brand, and product recalls. On the other hand, a high degree of variation often leads to higher scrap rates, higher necessity of inspection, and higher costs of precise and accurate machinery during production. Overall, variation is often expensive for the product manufacturer (Ebro, Krogstie & Howard 2015).

In order to reduce the final functional performance variation, it is commonly suggested to include variation risk management (VRM) (Thornton 2004) and robust design strategies (Ebro & Howard 2016) during the product development process). The VRM framework involves an identification, assessment, and mitigation of the variation risks, whereas the robust design principles contribute specific strategies to mitigate the variation risk during the design of the product.

In light of this, part features that are prone to variation and play a role in the final functional performance are termed key characteristics. A systematic process for the identification of key characteristics is consequently vital for the success of any VRM activities as it directs redesign efforts and/or allows for an informed prioritization of subsequent tolerance analysis tasks. Such a process should further be applicable and promote VRM in the early stages of the product development process since most of the total expected cost is accounted for by the early design decisions (Tan, Otto & Wood 2017).

1.1. Issue

In moving, multiple-state mechanical products (i.e., products where the engagement of interfaces, and thus of parts, continuously change during use, thus having multiple structural states (Andreasen, Hansen & Cash 2015) that are the specific configurations of interfaces between parts see definition later), it has been observed that it is difficult for the product development teams to create an overview of the behavior of the products. As a result, it is difficult for the design practitioners to identify the interfaces that are critical for the intended behavior and thus for the intended functions across the different structural states (Bjarklev, Mortensen & Ebro 2017; Sigurdarson, Eifler & Ebro 2018). There is simply a lack of a systematic and quantitative approach or tool for prioritizing the tolerance analysis tasks.

Zhang & Thomson (2016) showed that 'a growth in complexity increased effort and span time exponentially' in the product development process and that improved communication and collaboration in the development team contributes to reducing the effort and time spent.

The list of function-critical interfaces between parts that experience variation (i.e., key characteristics) at different structural states creates the basis for the tolerance analysis work done during the variation risk assessment stage of the VRM process (Thornton 2004; Bjarklev *et al.* 2017; Sigurdarson *et al.* 2018). The process of identifying, evaluating, and prioritizing the most critical interfaces for the tolerance analysis can be assigned to the preliminary analysis step in generic risk management, described in ISO 31030:2009 (International Organization for Standardization 2010, Section 5.3.5).

1.2. Research question and scope

This paper addresses the following research question:

> Can the complexity of the mode of action be related to variation risk and robustness issues, and is it consequently suited as an indicator for prioritizing the tolerance analysis tasks in the early stages of embodiment design?

The complexity of mode of action refers to the number of intended state changes and expected interactions and interfaces along the use cycle of the mechanical product that together define the behavior of the product. We define the mode of action in Section 3.

This paper focuses on the initial prioritization of the tolerance analysis tasks, i.e., the preliminary analysis in the variation risk identification stage (Thornton 2004; International Organization for Standardization 2010), which can roughly be assigned to early embodiment where preliminary layouts and part geometries are determined. In this stage, the physical placements and the geometry of the bodies of the design is being determined.

1.3. Structure of the paper

This paper is structured as follows: Section 2 summarizes current literature related to the topic of indicating variation risk and robustness issues in the early design phases. In Section 3, we detail the definitions and assumptions that form the basis of this research project. In Section 4, we describe the five-step procedure for calculating the Mode of Action Complexity Scores and describe how we applied it on a case study and how we evaluated the results against a high priority tolerance calculation list. The high priority tolerance calculation list is the list of tolerance calculations defined by the tolerance expert and the mechanical design team. These are deemed most relevant to verify since variations of the interfaces (whose variation will be analyzed with the calculations) are evaluated to have a relatively high likelihood of impacting the functionality of the design.

In Section 5, we present the Mode of Action Complexity Scores of the bodies and structural state transitions of the case study, and we also present and compare with the appearance counts from the high priority tolerance calculation list. In Section 6, we discuss the potential sources of error in the findings, the contributions of this work, and areas of future work. Finally, we summarize the findings of this paper in Section 7.

2. Existing evaluation methods and principles

In literature, we find approaches from robust design and variation evaluation for pre-evaluating the variation risk.

2.1. Early robustness

Work has been done to bring robustness into the early stages of the product development process. For example, Jugulum & Frey (2007) did a thorough patent search and classification for identifying common robustness strategies that can be implemented in the concept design stage. They divided the approaches into the categories of a P diagram as a means of modifying the input signal, output signal, control factors, and noise sources. Ebro & Howard (2016) described several robust design principles that can be applied at different stages of the product development process and aim to reduce the sensitivity of the functional performance to variation of the design parameters. Andersson (1997) discussed that in the conceptual design stage, the lack of an embodied design renders it difficult to make experiments with the design with the purpose of establishing the transfer functions (i.e., the functions among the design domains of customer satisfaction, functional performance, design parameters, and production parameters). Andersson elaborated on the principles of clarity, simplicity, and safety for increasing robustness of the design during the conceptual design stage and discussed the importance of system design for achieving robustness. As a side note, Andersson argued that simplicity of the mode of action will typically lead to a less variation sensitive design since 'the less number of functions and sub-processes, the less number of ways for noise to enter the system' (Andersson 1997, Section 3.2).

These approaches suggest useful principles for improving the robustness, but they do not measure how robust the design is or where to apply the principles in the design.

2.2. Robustness indicators

Göhler, Eifler & Howard (2016) made a thorough literature review on the existing robustness metrics. They categorized the identified robustness metrics into four classes: sensitivity robustness metrics, size of the feasible design space, expectancy and dispersion measures, and probability of functional compliance. All the identified robustness metrics require knowledge of the relation between design parameters and functional performance. Furthermore, the identified robustness metrics typically describe the degree of sensitivity between design parameters and functional performance. Newer literature shared a similar focus on either building the transfer functions (increasing the accuracy) or optimizing the design based on this (Steinfeldt & Braun 2016; Liu 2017; Wang *et al.* 2017; Xu *et al.* 2018). Subsequently, Göhler & Howard (2015) and Göhler, Frey & Howard (2017) proposed a contradiction index, CI, where the complexity of a mechanical product is related to its robustness. In their work, they define complexity to be 'related to the degree of coupling of the functions in the design [...] and the level of contradiction of the couplings' (Göhler *et al.* 2017).

Extending the general idea of couplings between functional requirements (Suh 2001), the contradiction index framework evaluates the contradicting influence of design parameters on required product properties. The contradiction index can be aggregated to part level, organ level, and functional requirement level. The contradiction index can be used at an early point of the product development process, but also requires knowledge about the influence of the design parameters and the properties on the functional performance. This means that the design needs to be mature enough that the specific design parameters can be determined in order to conduct the evaluation. Furthermore, it does not include the shifts of interfaces (structural state transitions), which may be required for the product to function as intended.

Common for the robustness indicators is consequently that they describe *how* geometrical variation impacts the functionality of the mechanical product. Using the indicators typically requires knowledge about the impact of the geometrical variation on the functional performance, i.e., knowledge about the transfer functions. Generating the transfer function is typically done with physical experiments or computer simulations, which requires a certain maturity of the product design that is typically obtained at later stages of the design process (Andersson 1997). Furthermore, the available indicators are not considering the structural composition of mechanical systems, i.e., they do not indicate which parts or structural state transitions will be most affected by geometric variation.

2.3. Evaluation of variation

Goetz, Schleich & Wartzack (2018) proposed a method for collecting the semantic information of a conceptual design, which was combined with oriented graph representation inspired by the work of Dantan *et al.* (2005), in order to give an initial estimation of the expected variation of the joints of the system and evaluate and compare different concepts. Malmiry *et al.* (2016*a*,*b*) proposed a method for decomposing the function behavior and structure of the design in order to define the functional tolerances. They did this by mapping the energy flows in the system and identifying the characteristics that were responsible for the desired properties, as defined by Weber (2005). This method is used to reduce the epistemic uncertainty, i.e., to increase the knowledge about the system, and uses a top-down approach to map the characteristics that should be in focus of the tolerancing process to achieve the desired properties. Both methods provide efficient tools for mapping the structure to the performance of the product and can be applied early in the product development process in the conceptual design stage. However, they focus mostly on single structural states and the subsequent assembly structures.

The failure mode, effects, and criticality analysis (Apollo Reliability and Quality Assurance Office 1966) and advanced failure modes and effects analysis (Eubank, Kmenta & Ishii 1997) could include variation considerations as an input to the estimation of the probability of failure, but they do not describe how to evaluate the product in this perspective. This aspect was introduced in the variation mode and effect analysis (VMEA) proposed by Chakhunashvili, Johansson & Bergman (2004), which evaluates the variation risk on the key product characteristics and focuses on the variation impact on the important functions. It scores the impact, variability, and sensitivity on the levels of key product characteristics, sub-key product characteristics, and noise factors. A variation risk priority number is aggregated and calculated for the sub-key product characteristic. The VMEA does not compare the relative importance of the key product characteristic. The VMEA provides a systematic procedure for practitioners to decompose and evaluate the variation risk of the key product characteristics. The risk is identified top-down, meaning that a practitioner has to start at the important functions and backtrack (typically using his or her experience) to what could influence these functions. If practitioners do not think of a given potential variation or failure mode, then this will not be included in the analysis.

2.4. Modeling variation in mechanical assemblies

Valuable contributions in the field of computer-aided tolerancing (CAT) addressed the evaluation of variation. For example, Söderberg & Johannesson (1999), Söderberg & Lindkvist (1999*a*,*b*) and Johannesson & Söderberg (2000) evaluated the robustness of a product according to how the embodied parts are located with respect to each other. Identifying these geometrical relations between parts allows for an optimization of robustness according to the principles of axiomatic design. Defining these relations in computer-aided design (CAD) tools allows for a subsequent statistical analysis of the expected variation. Similarly, Mantripragada & Whitney (1998) describe the positioning relationships (mating features) between the parts in assemblies, through which variation will propagate. Tolerance analysis can be based on these features and the chains that they create.

The design structure matrix (DSM) (Eppinger & Browning 2012) is typically used for mapping the relations (interfaces) between parts of the product. Part-to-part mapping can be used for evaluating the degree of coupling and calculating the sensitivities of the interfaces between parts in the assembly, as suggested by Johannesson & Söderberg (2000). There, the CAT system simulates variations of the locating points in small increments and thereby estimates the sensitivity toward variation. These aforementioned contributions emphasize the relevance of analyzing the physical embodiment and the contact surfaces between parts in the early stages of the development process in order to assess the variation that will occur in the final product. However, the contributions focus less on systematic descriptions of what happens in mechanisms when they transition between structural states and how variation affects these transitions. Namely, we see a gap in existing literature for evaluating the variation across the collection of structural states of the product.

Available commercial CAT tools were reviewed by Prisco & Giorleo (2002) and later by Sigurdarson *et al.* (2018). Both contributions describe that CAT systems in many cases are capable of doing advanced tolerance calculations. Yet, several essential elements typically need to be defined manually, e.g., the datums and relations between elements in the assemblies. Furthermore, the user often needs to know beforehand which features need to be analyzed. This indicates that the task of identifying and prioritizing which calculations to perform is still an area that is not well supported by current commercial CAD tools.

2.5. Product complexity

Weber (2005) divided complexity into five dimensions with two of them being numerical and relational complexity, referring to the 'number of components in a product or system' and the 'number of relations and inter-dependencies between the components,' respectively. Weber argued that while numerical complexity is covered well by existing tools and computer-aided systems, the field of relational complexity still requires a definition for which types of relations should be captured and which IT concepts should be used for capturing them.

Similar to Weber (2005), Sinha & Suh (2018) categorized complexity of engineering systems into structural complexity, including components, interfaces, and architecture topology, and dynamic complexity, including interaction structure and interaction uncertainty. They describe dynamic complexity as the complexity of what the product does (behavior with regard to the functions), rather than complexity of the form of the product (as is the case for structural complexity). Sinha and Suh focus mainly on the structural complexity in the field of product architectural optimization while focusing less on the dynamic complexity, and neither researcher focuses on the geometrical variation.

Suh (2005) defined complexity as 'the measure of uncertainty in satisfying the FRs [functional requirements] within the design range,' i.e., how sure we are that the product does what it is supposed to with the given design.

Suh (2005) introduced the time aspect into complexity by categorizing it into time-independent and time-dependent complexity. Time-independent complexity is further divided into real complexity, describing the uncertainty related to the actual probability of not achieving the functional requirements (similar to the concept of aleatory uncertainty) and imaginary complexity, describing the uncertainty related to the lack of knowledge of the design itself (similar to the concept of epistemic uncertainty). Time-dependent complexity relates to the accumulation of uncertainties through time, dividing it into combinatorial complexity, where the accumulation increases endlessly, and periodic complexity, where the accumulated uncertainties are reset after specific periods.

Summers & Shah (2010) identified three main threads in complexity measurement across literature: size (counting elements such as design variables, functional requirements, constraints, and sub-assemblies), coupling (connections between variables), and solvability (the product's ability to satisfy the problem). Whereas the size of the system seems related to Weber's (2005) numerical complexity term or Sinha and Suh's structural complexity term, couplings of the system seem related to Weber's relational complexity term or Sinha and Suh's dynamic complexity term. Suh's (2005) definition of complexity would fit into the solvability of the system category.

In this research project, we aim to describe the aleatory uncertainty (real complexity) related to the numerical and relational complexity of moving mechanical products due to their parts and interfaces, describing how these interfaces change over time and thus including the time-dependent periodic complexity of the product as it moves through its use cycle.

3. Theoretical background

As shown previously, existing tools are not sufficient for the systematic prioritization of multi-stage mechanisms. In order to answer the research question, which is for developing a corresponding quantitative indicator, we use function reasoning and mode of action description (Andreasen *et al.* 2015) and the Variation Effects and Aspects of Mode of Action (VEAMoA) model (Bjarklev *et al.* 2018) to build upon.

3.1. Function reasoning and mode of action

In order to describe how the variation influences mechanical products, a generically applicable description of how the product works is required. This abstract product representation has to link the design intent with the description of the actual product structure and, in this way, builds a framework for describing potential risk of variation.

For this purpose, we use a series of concepts and terms presented in Table 1, most of which are adapted from the definitions by Andreasen *et al.* (2015). We use the example of a retractable ballpoint pen to exemplify the terms.

The designers create the design with a certain intended mode of action, which creates a certain intended behavior, which in turn delivers certain intended functions. The bodies or parts of the product create the action conditions by being present with given states and given interfaces at given points of time, which allow interactions between the bodies. These interactions cause state changes of the bodies involved. The state changes of the bodies may cause new interfaces to occur, thereby creating new structural states in the product and new action conditions. The mode of action is the physical building blocks of the functions and describes how a product works.

3.2. Variation effects and aspects of mode of action model

The VEAMoA model (Bjarklev *et al.* 2018) is an interpretation and application of the generic mode of action description in the context of designing purely mechanical products. The concretization of the aspects of mode of action further allows for a symbolic representation of the mode of action as a means to ease the communication of the concept and how it is intended to work within the company. This is explained in Bjarklev *et al.* (2018).

In the VEAMoA model, interactions are interpreted as information transfers and force and energy transfers between parts. State changes of bodies are interpreted as part movement or deformation. Interfaces are interpreted as the

Table 1. Description of key terms used in this paper

Term	Description	Example: retractable ballpoint pen
Function	'Functions are a product or activity's ability to do something actively or be used for something, i.e., deliver an effect' (Andreasen *et al.* 2015, p. 270).	A function of the pen is to hide and expose the writing tip.
Behavior	'Is the complex of state changes that occur in an activity or device based on natural phenomena' (Andreasen *et al.* 2015, p. 278). Every product has a certain behavior, some of which will be intended and will deliver the functions. The structural state transitions also form part of the behavior.	The behavior is the movements of the tip, cartridge, button, and compression of the springs.
Mode of action	Is the phenomena where 'effects from the surroundings and interactions between the action conditions realize natural phenomena resulting in a desired effect' (Andreasen *et al.* 2015, p. 276). The mode of action describes the cause of the intended behavior and consists of the intended external effects and interactions between the bodies that cause the following intended state changes and effects.	The forces and energy transfers between the trigger mechanism and the cartridge, which cause the writing tip to retract or extend, form part of the mode of action for the pen. It is the reason behind the movement of the parts and, thus, the desired behavior.
Action conditions	The action conditions 'are the arrangement of external effects and interactions between bodies, which create the physical conditions for utilizing a natural phenomenon to create state changes, and subsequently effects' (Andreasen *et al.* 2015, p. 277). It is the setup for allowing the mode of action.	The action conditions of the pen are the arrangement and placement of the trigger mechanism, the cartridge, the springs, and the forces that travel through the product at specific points in time. They are also the absence of any surfaces or features that may hinder the intended movement of the parts.
State change	A state 'is a description of an entity in terms of parameters (physical quantities)' (Andreasen *et al.* 2015, p. 278). A state change is thus the change of these quantities and is caused by interactions between bodies based on natural phenomena. It is thus the gain or loss of internal energy, material, or signal. 'An effect is a state change in a mode of action [...], which leads to interaction with other entities' (Andreasen *et al.* 2015, p. 276).	For the trigger button of the pen, a state change is the change in position (acceleration) relative to the housing, e.g., when the button is pressed by the user. Alternatively, a state change of a spring could be the compression or decompression when the trigger button is pressed.
Interactions	The propagation of effects between bodies. Interactions are the transfer of energy, forces, information, or material between adjacent bodies. The interactions define the state changes of each body and as such are part of the action conditions (Andreasen *et al.* 2015, p. 288).	In the pen, the trigger button interacts with the cartridge by transferring forces and energy to it. The user interacts with the trigger button by transferring forces to it. The housing guides the movement of the cartridge through forces on the side of the cartridge, thus interacting with this part.

Table 1. (continued)

Interfaces	The physical places or planes where interaction between bodies occur (Parslov *et al.* 2016), and their presence or absence are also part of the action condition. Interfaces belong to the embodiment of the solution and are defined by the features of the parts (Andreasen *et al.* 2015, p. 295).	In the pen, the interface between the writing tip and the paper is where the surface of the ball and the surface of the paper touch each other. The interface between the trigger button and the user is the surface of the button and the surface of the user's finger that touch each other, allowing the interaction of a force transfer.
Bodies	The basic entities in the design, which are often directly translated into the individual parts in the embodiment design. Andreasen et al. describe the following: 'Bodies and their interactions become the link to the part structure, which mirrors and realizes the action' (Andreasen *et al.* 2015, p. 275).	Examples of bodies in the pen are the cartridge, the housing, and the spring. Any entity that moves or deforms is one.
Part	'is a material element of a product. The part materializes the bodies and their interactions and is characterized by its form, material, dimensions, and surface qualities' (Andreasen *et al.* 2015, p. 291).	Examples of parts in the pen are the trigger button, the cartridge, the writing ball, or the spring.
Use cycle	We define the use cycle as the collection of all structural states and transitions that the mechanical product goes through in its use.	The use cycle of a pen is: *retracted tip, button in neutral position – exposed tip, button pressed – exposed tip, button in neutral position – exposed tip, button pressed – hidden tip, button in neutral position*. Each of the steps is regarded as a structural state.
Structural state transitions	A structural state is a specific configuration of the bodies and their interactions in a system. During a structural state transition, the interactions and interfaces of the system shift (change engagement) due to state changes of the bodies in the system (Andreasen *et al.* 2015, p. 287). A structural state is the configuration of bodies and their interactions and interfaces along the use cycle of the product, where most bodies are at rest (i.e., they do not experience state change).	An example of a structural state transition of the pen is the process of going from *hidden tip with button in neutral position* to *exposed tip with button pressed.*

place of contact between two parts, typically the geometrical surfaces that touch each other through which forces and energy are transferred. The interfaces depend on the relative positions of the surfaces defined by the parts. New interfaces are created when surfaces are positioned differently as a result of a part movement or deformation, which is a result of a change in the force transfer equilibrium and energy flow of the system. Thus, the mode of action may be described as 'interaction $\Rightarrow$ state change $\Rightarrow$ interface $\circlearrowleft$' cycle or causal chain. Each of the aspects of mode of action (and thus links in the causal chain) may be subject to variation, and the variation of one aspect may lead to variation in the subsequent aspect(s). Similarly, each of the aspects of mode of action may be controlled, and

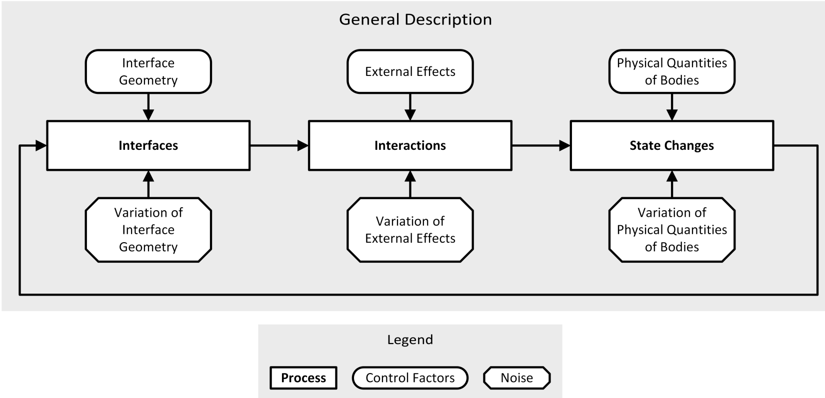

Figure 1. Triple-parameter diagram illustrating the introduction points and propagation of variation in the mode of action of the product. Similarly, controls may be introduced at each aspect of the mode of action and also propagate to the following aspects. The triple-P diagram describes the general aspects of mode of action.

the control of each aspect propagates to the following aspect of the mode of action. We illustrate this in the triple-parameter diagram shown in Figure 1.

From the VEAMoA model, we obtain the following way of describing how variation is transferred between parts of the mechanical product through the mode of action. The degree of robustness of a product determines to what extent variation will be transferred from one aspect of mode of action to the next.

(i) Variation of an interface causes variation of the subsequent interactions related to this interface. For example, if two surfaces on two different parts that are intended to meet and transfer a force in a certain direction from one to the other experience geometrical variation, the force will likely be transferred in a slightly different direction than intended.
(ii) Variation of an interaction causes variation in the subsequent state changes and of the propagation of effects. For example, if a force is applied on a part in a slightly different direction than intended, the part will likely move in a different direction than intended.
(iii) Variation of a state change causes variation in the subsequent interfaces and interactions created by this state change. For example, if a part moves differently than intended, then the part will likely make contact with the neighboring part differently than intended.

3.3. Assumptions

Our research question is based on the following assumptions, which link the Mode of Action Complexity with the expected geometrical variation and build upon the VEAMoA and mode of action description.

(1) *The more interactions and following state changes a body experiences during a structural state transition, the higher the likelihood is that the mode of action related to the body varies from what was intended.* For every interaction in the mode of action of the mechanical product, variation may be introduced and transferred to the next step of the mode of action. Seen from the perspective

of the individual body, the more that body experiences, the higher the risk will be that variation will affect the intended state changes of the body. Thus, a body that interacts few times with neighboring bodies during a structural state transition will experience less variation in its final state than a body that interacts many times with neighboring parts.

(2) *The more bodies that contribute to defining the state change of a body (through interactions), the higher the likelihood is for the state change of the body in question to vary from the intended, as each interaction may vary.* The more bodies that the individual body must come in contact with during a structural state transition, the higher the risk of variation in the mode of action related to that body. Each body must be in the right place at the right time (action conditions) in order to complete the right interactions and state changes (mode of action). The more bodies that must be in place for the mode of action to go as intended, the higher the risk of variation of the mode of action. Thus, a body that interacts with a single or few bodies will experience less variation in its final state than a body that interacts with many different bodies since the variation of the states of the neighboring bodies may introduce variation to the body in question through the interactions.

(3) *The more that must happen (action conditions and elements in the mode of action) in a mechanism during a structural state transition, the more likely the structural state transition in question will experience variation.* If many action conditions need to be present and many steps of the mode of action must happen, and if variation can be introduced in every element, then what is intended to happen in the entire structural state transition will likely vary. A product that has many bodies that need to move (change state) at the same time or during the same structural state transition will experience more variation in that structural state transition than a product that has few bodies that need to move at once or during a state transition. This assumption sees the variation from the point of view of the entire product rather than from a single body.

4. Method

Based on the VEAMoA model, we suggest an approach for deriving an indicator in the early embodiment design stage for prioritizing the subsequent tolerance analysis. The approach is detailed below and tested with a case study.

Following the VEAMoA model, the design practitioner would have to trace each interface, interaction, and state change that happens to each part or body. Practically, it would be time-consuming for the designers or tolerance experts to account for each interaction that occurs in the given system. Since the approach is intended for use in the early embodiment design stage, changes to the design happen often, and any tool for this stage should be applicable correspondingly quickly. Therefore, in order to simplify things, the procedure that we suggest and apply in this paper relies simply on counting the movements or deformations (state changes), the intended changes in engagement (interactions) between parts, and the potential unwanted engagements (interactions) between parts. This is explained in detail in the following procedure.

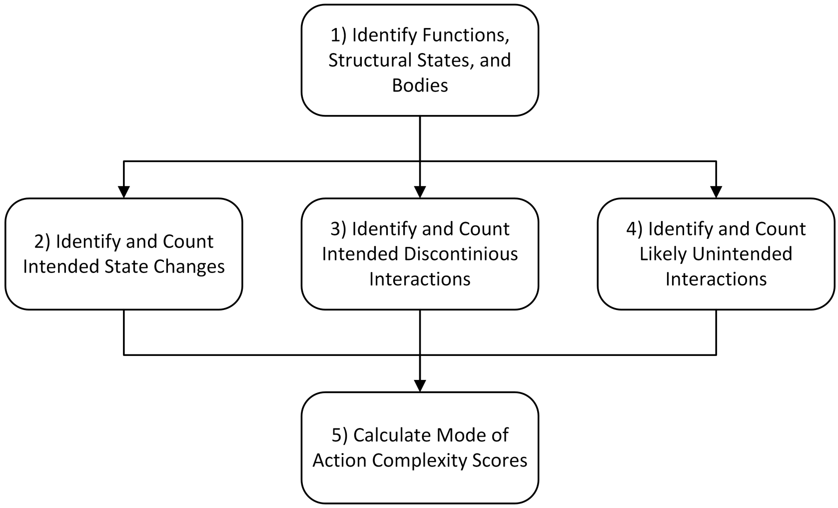

Figure 2. Five-step procedure for generating the Mode of Action Complexity Scores.

4.1. Procedure

We propose a new metric for evaluating the complexity of the mode of action of a mechanical product in relation to the expected variation. In order to determine the Mode of Action Complexity Metric for a given mechanical design, we suggest the following steps (overview in Figure 2).

4.1.1. Functions, structural states, and bodies

We define the functions, structural states, and bodies of the system.

The type of mechanical products that we address in this work has to go through a series of structural state transitions in order to deliver its function.

Structural states are points in time in the use cycle where no or few parts are changing state and force equilibrium is typically reached. The structural states must also be reasonable from a user perspective. The structural states transition is the action that happens in between the structural states, and this is therefore of interest from a mode of action description perspective.

The bodies are typically parts (or smaller sub-assemblies, where the parts included do not move relative to each other during the entire use cycle).

4.1.2. Parameter 1: number of intended state changes

For each structural state transition, we identify and count the intended state changes that each body experiences.

We count the intended changes that are supposed to happen to the states of the bodies. Several state changes may happen during a structural state transition. Structural state transitions and state changes should not be confused with each other.

The state changes are defined by the interactions with other parts, including the interactions through already existing interfaces, and is thus representative of the complex of interactions in the system.

In our case study described below, the state changes are the (continuous) acceleration or deformation of the parts, and each change in direction is counted as a new state change. Continuous deformation of springs or elastic bodies is also counted as a state change, and change in direction of deformation is counted as a new state change. Finally, loss or gain of material to a body is also counted as a state change.

Induction or transfer of an electrical charge to a body would also count as a state change.

We denote the number of intended state changes s_{ij} for each body i for each structural state transition j. This parameter describes the amount of desired effects (action) that is required in the structural state transition.

4.1.3. Parameter 2: number of intended discontinuous interactions

For each structural state transition and each body, we identify and count the neighboring bodies that engage or disengage with the body. Intended interactions are ascribed as both parts interacting so that there is no doubt whether an interaction has been accounted for or not.

Bodies that have discontinuous interactions with each other either gain and/or lose physical contact (interface) with each other during a structural state transition. This way of counting is based on the assumptions that changing interfaces between bodies have a higher likelihood of varying than continuous interfaces and that engagement and disengagement between different bodies have the highest general likelihood of failing.

In the case study described below, we count if a body comes into physical contact with a new body or loses physical contact with a body that it was previously in contact with. We count for all the new bodies that the given body comes into contact with or loses contact with. If a body comes within a magnet's magnetic field so that the magnetic field significantly influences the state of the body, this would also count as a new contact.

Interactions with the user of the product are also counted. The user will typically give input to the mechanical product through an interaction. This interaction is also a point where variation can be introduced and is, therefore, counted toward the complexity.

We denote the number of intended discontinuous interactions d_{ij} for each body i for each structural state transition j. This parameter contributes to describing the amount of action conditions in the system.

A continuous interaction would, in this context, be a contact between two parts which is kept during a structural state transition, even though the points on the surfaces of the parts that touch change or if the interaction changes (e.g., if an energy flow is increased or decreased during the structural state change).

4.1.4. Parameter 3: number of likely unintended interactions

For each structural state transition, for each body, we identify and count the neighboring bodies that may have unintended interaction with the body that may hinder the intended state change. Unintended interactions are ascribed as both parts interacting so that there is no doubt whether an interaction has been accounted for or not.

Bodies may interact unintentionally with each other, hindering the intended state changes of the bodies. If the surface of a body is placed in such a way that it may (due to variation) cause the intended state change (e.g., part movement or deformation) of the given body to fail or vary, the body is counted. This means that the designer must evaluate whether the distance between two surfaces during the structural state transition is smaller than the expected geometric variation of the surfaces. At the stage of embodiment design, the general size of the parts are known to the designer. By the designer having an idea of the final material and the manufacturing method of the part, the order of magnitude of geometrical variation can be estimated at an early point of the embodiment design stage. This estimation of the geometrical variation, together with the knowledge about the mode of action of the product, forms the basis for evaluating whether an unintended interaction between parts is likely.

For example, if a body is intended to move close to a feature on another part without touching it but the feature or the size of the given body is likely to vary so that the feature blocks the passage of the body, then the body with the feature is counted to the likely unintended interactions that the given body experiences. Alternatively, if a rod needs to slide within a cylinder and either the size of the rod or the cylinder or the friction coefficient are likely to vary so that the rod cannot move as intended, the cylinder is counted to the score of the rod, and the rod is counted to the score of the cylinder.

We denote the number of likely unintended interactions u_{ij} for each body i for each structural state transition j. This parameter contributes to describing the amount of action conditions in the system.

4.1.5. Mode of action complexity scores

We collect the scores given for the bodies $[1; n]$ and for the structural state transitions $[1; m]$ in the matrices **S** (intended state changes), **D** (discontinuous intended interfaces), and **U** (likely unintended interfaces):

$$\mathbf{S} = \begin{bmatrix} s_{11} & \dots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{m1} & \dots & s_{mn} \end{bmatrix}, \tag{1}$$

$$\mathbf{D} = \begin{bmatrix} d_{11} & \dots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \dots & d_{mn} \end{bmatrix}, \tag{2}$$

$$\mathbf{U} = \begin{bmatrix} u_{11} & \dots & u_{1n} \\ \vdots & \ddots & \vdots \\ u_{m1} & \dots & u_{mn} \end{bmatrix}. \tag{3}$$

For every structural state transition j, we sum the parameter scores of the n number of bodies. This gives the Transition Mode of Action Complexity Score T_j for each of the structural state transitions j:

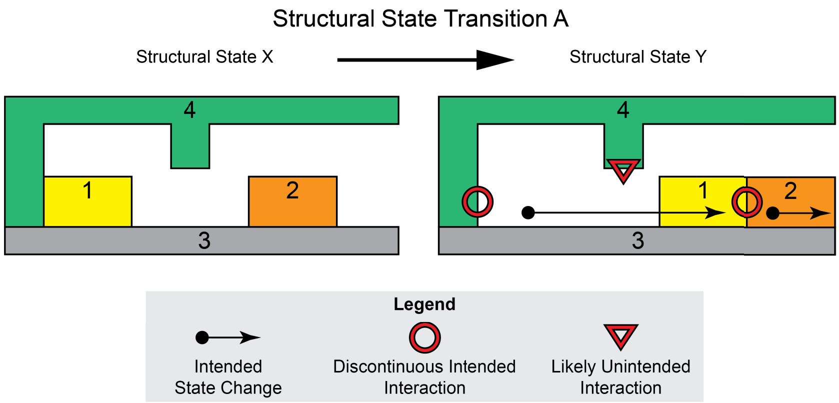

Figure 3. Simple case example illustrating a single structural state transition. Part 1 moves, losing contact with Part 4 and creating contact with Part 2 (emphasized with red circles). These are two discontinuous intended interactions, which are ascribed to Parts 1, 2, and 4. As a result of the interaction with Part 1, Part 2 also moves. The movements of Parts 1 and 2 are counted as state changes. The feature of Part 4 (emphasized with a red triangle) is judged to be close enough to the path of Part 1 that it is counted as a likely unintended interaction and is ascribed to both Parts 1 and 4. Points are given to the parameters accordingly; see Table 2.

$$\sum_{i=1}^{n} (s_{ij} + d_{ij} + u_{ij}) = T_j. \tag{4}$$

For every body i, we sum the parameter scores of the m number of structural state transitions. This gives the Body Mode of Action Complexity Score B_i for each of the bodies i:

$$\sum_{j=1}^{m} (s_{ij} + d_{ij} + u_{ij}) = B_i. \tag{5}$$

The Transition Mode of Action Complexity Scores T_j are compared and used for prioritizing the structural state transitions so that the following tolerance analysis will focus on the most critical structural state transitions. The Transition Mode of Action Complexity Scores build upon the third assumption (described in Section 3.3) since the complexity is described from the point of view of the structural state transitions of the entire product.

The Body Mode of Action Complexity Scores B_i are similarly compared and used for prioritizing the most critical bodies and build upon the first and second assumptions (described in Section 3.3) since the complexity is described from the point of view of the single bodies.

Figure 3 and Table 2 illustrate a simple use case of how to score and calculate the Mode of Action Complexity of a hypothetical design.

4.2. Application to case study

We use a new product design from Novo Nordisk A/S to illustrate and test the approach. The product design chosen is an insulin injection device that is both highly integrated and has several structural state transitions along its use cycle.

Table 2. Calculation of the simple example shown in Figure 3 illustrating the Mode of Action Complexity Scores for Parts 1–4 at structural state transition A. Part 1 has the highest Body Mode of Action Complexity Score ($B_1 = 4$), meaning that this part and its interfaces should have the highest priority in the subsequent tolerance analysis

	State changes	**Discont. intended interactions**	**Likely unintended interactions**	**Sum**
Part 1	$s_{1A} = 1$	$d_{1A} = 2$	$u_{1A} = 1$	$B_1 = 4$
Part 2	$s_{2A} = 1$	$d_{2A} = 1$	$u_{2A} = 0$	$B_2 = 2$
Part 3	$s_{3A} = 0$	$d_{3A} = 0$	$u_{3A} = 0$	$B_3 = 0$
Part 4	$s_{4A} = 0$	$d_{4A} = 1$	$u_{4A} = 1$	$B_4 = 2$
Sum	$s_A = 2$	$d_A = 4$	$u_A = 2$	$T_A = 8$

The names of the bodies and the structural state transitions have been anonymized due to confidentiality. The bodies are named 1–24, and the structural state transitions are named A–F. All parts of the concept are included in the analysis. Sub-assemblies, where the parts do not move relative to each other during the entire use cycle, are regarded as single bodies.

The structural state transitions of the device involve preparing the device, setting the dose, injecting the dose, and preparing to store the device. The structural state transitions chosen for this case study were clusters of the states that the product development team had defined in advance. Clustering the structural states was done in order to adhere to the principle of most bodies being in rest, while departing from the predefined structural states improved the comparability of the results with the tolerance analysis work for evaluating the approach, as described below.

Each body for each structural state was examined and scored according to the parameters described above. The scores are presented in Figure 4, in Section 5.

4.3. Evaluation of approach

We evaluate our approach by comparing the Mode of Action Complexity Scores of the parts, the structural state transitions with the parts, and the structural state transitions that are involved in the high priority calculations from the actual tolerance analysis work done by the engineers in the same product development project that was chosen as the case study in this research. This is possible because the chosen case study is at a later stage than what our approach is intended for. Thus, the fundamental tolerance analysis work has already been performed.

The high priority tolerance calculations are the calculations that focus on features or interfaces in the design whose variation will have a particularly high likelihood of impacting the functionality of the product. The high priority tolerance calculations are defined by the mechanical design team and the tolerance expert based on an initial evaluation of the design, including the relative proximity of the interfaces, the known likely variation from the manufacturing methods, knowledge about previous similar designs, and variation issues. These are typically listed in the beginning of the tolerance analysis work when the design reaches a certain maturity often in the beginning of the embodiment design phase. Each tolerance calculation focuses on the interface between two parts at a specific point in time (structural state).

By collecting the list of high priority tolerance calculations and counting the times that specific bodies as well as structural states and transitions appear in this list (appearance count), a series of the most relevant bodies and structural state transitions is aggregated. Calculations that were done for the same interface but at different temperatures are regarded as a single calculation since the difference of temperature is not within the scope of this research project and it accounts for the same relative position of the bodies.

The bodies and structural state transitions with the highest counts from the high priority calculation list are regarded as the most critical for this research project. Thus, we can compare the most critical bodies and structural state transitions identified with our approach with the most critical parts and structural state transitions identified by the engineers involved with the project.

In order to compare the Mode of Action Complexity Scores with the appearance count in the high priority calculations, each body and structural state transition is ranked according to the score and the count. Furthermore, the score percentages and the count percentages are calculated so that the scores and counts may be evaluated against each other. The score percentage for each body or structural state transition is the score received in relation to the total score of all the parts or all the structural state transitions. Similarly, the count percentage is calculated by the appearance count of each body or structural state transition relative to the total count of all bodies or structural state transitions.

5. Results

Figure 4 shows the scoring of the individual bodies for each structural state transition for each parameter. The figure shows that in structural state transitions A, C, and F, most of the points were given to a certain group of bodies of the device, while the points were distributed more evenly across the device in structural state transitions D and E. Bodies like Body 18 experience many state changes during the use cycle but do not have many discontinuous intended interactions or likely unintended interactions. This means that the state changes of Body 18 come from bodies that are in constant contact with the body, yet it is isolated enough (has enough clearance) from other bodies that there is a low risk of the other bodies interfering with the intended state changes. Body 17 is removed from the device at structural state transition A and does, therefore, not appear in the rest of the structural state transitions.

Tables 3 and 4 show the resulting Mode of Action Complexity Scores for the bodies and for the structural state transitions, respectively. The tables also include the resulting appearance count of each body and structural state transition (respectively) from the high priority tolerance calculation list. The Mode of Action Complexity Scores and the appearance counts are compared by analyzing the percentage of scores or counts that each body received. Furthermore, the scores and the counts of each body and structural state transition lead to ranking placements, which are also compared in the respective tables (Tables 3 and 4).

Comparing the Body Mode of Action Complexity Score with the appearance count, the average absolute percentage point difference is calculated to be 2.7

Structural State Transition	A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F		
Body	New State Changes pr. Body						Sum	Discontinious Intended Interactions pr Body						Sum	Likely Unintended Interactions pr Body						Sum	Body MoA Complex.
1	0	0	0	0	0	0	0	0	0	0	1	1	0	2	0	1	0	1	2	0	4	6
2	0	2	0	2	0	0	4	0	1	0	1	0	0	2	0	0	0	0	0	0	0	6
3	0	0	0	2	1	0	3	0	0	0	1	1	0	2	0	1	0	1	1	0	3	8
4	0	1	0	2	1	1	5	0	0	0	0	0	0	0	0	2	0	1	1	0	4	9
5	0	1	0	2	1	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
6	0	1	0	1	0	0	2	0	0	0	0	0	0	0	0	1	0	1	1	0	3	5
7	1	1	0	2	1	1	6	0	0	0	1	1	0	2	0	1	0	1	2	0	4	12
8	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
9	0	1	0	0	0	0	1	0	1	0	1	1	0	3	0	0	0	1	1	0	2	6
10	0	0	0	1	1	0	2	0	0	1	0	0	1	2	0	0	1	1	1	0	3	7
11	0	0	0	1	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2
12	0	0	0	0	0	0	0	1	0	0	0	0	0	1	2	0	1	1	1	1	6	7
13	2	0	0	0	0	0	2	1	0	0	0	0	0	1	3	0	1	1	1	1	7	10
14	1	0	0	1	0	0	2	1	0	0	0	0	0	1	0	0	0	0	0	0	0	3
15	3	0	1	1	1	0	6	2	0	0	0	0	0	2	2	0	0	0	0	0	2	10
16	2	0	3	1	1	3	10	1	0	1	0	0	1	3	2	0	3	2	2	2	11	24
17	2	-	-	-	-	-	2	2	-	-	-	-	-	2	1	-	-	-	-	-	1	5
18	2	0	3	1	1	3	10	0	0	0	1	1	0	2	0	0	1	1	0	0	2	14
19	3	0	2	1	1	1	8	1	0	0	1	0	0	2	2	0	2	1	0	2	7	17
20	2	0	0	0	0	0	2	3	0	0	0	0	1	4	2	0	2	2	0	1	7	13
21	2	0	0	0	0	0	2	1	0	0	2	1	1	5	3	0	2	2	0	2	9	16
22	3	0	0	0	0	0	3	2	0	0	0	0	0	2	1	0	0	0	0	0	1	6
23	1	0	1	1	1	1	5	0	0	0	0	0	1	1	2	0	1	2	0	1	6	12
24	0	1	0	1	0	0	2	0	1	0	1	0	0	2	0	2	0	2	1	0	5	9
Number of Bodies	24	23	23	23	23	23		24	23	23	23	23	23		24	23	23	23	23	23		
Sum	24	8	10	21	10	11		16	3	2	10	6	5		20	8	14	21	14	10		
Structural State Transition MoA Complexity															60	19	26	52	30	26		

Figure 4. Scoring the Mode of Action Complexity for bodies and the structural state transitions.

percentage points, while the minimum is 0 percentage points and the maximum is 6 percentage points. The average absolute rank difference is calculated to be 2.3, while the minimum is 0 places and the maximum is 7 places.

Comparing the structural state transition Mode of Action Complexity Score with the appearance count, the average absolute percentage point difference is calculated to be 3.4 percentage points, while the minimum is 1 percentage point and the maximum is 7 percentage points. The average absolute rank difference is calculated to be 0.7, while the minimum is 0 places, and the maximum is 2 places.

6. Discussion

6.1. Result differences

We note that particularly Body 21, Body 15, and Body 1 are outliers by having an absolute percentage point difference of 6, 5, and 6, respectively. These three cases had more attention in the high priority tolerance calculation list than what was estimated by the Mode of Action Complexity Score. These three bodies are especially relevant for the dosing accuracy of the device, and the product development team may have regarded them as relatively more important for this property than the rest of the bodies, thus adding more calculations for these products to the high priority calculation list.

Body 1 is the frame component, which was used as the reference frame for all other movements (state changes) in the device. Since it is the reference frame, it does not seem to move (and does, therefore, not experience state changes) in the system. Thus, it scored low when counting the state changes. In this case study, the frame component experienced several intended *continuous* interactions, which may have increased its general score if counted. This indicates a reason to include continuous interactions in future versions of the Mode of Action Complexity Score. A correction factor should be added to the Mode of Action Complexity Score of the reference frame in order to compensate for this.

Structural state transitions D and C likewise have higher absolute percentage point differences of 6 and 7, respectively. Structural state transition D is also important for the dosing accuracy of the device and may similarly have received more attention from the product development team. Most of the tolerance

Table 3. Results of Mode of Action Complexity Scores and high priority tolerance calculation appearance count for bodies

Body	Mode of Action Complexity Score	Score percentage [%]	High priority appearance count	Count percentage [%]	Absolute percentage point difference	Rank (score)	Rank (count)	Abs. rank difference
16	24	11	8	7	4	1	5	4
19	17	8	13	12	4	2	2	0
21	16	8	15	14	6	3	1	2
18	14	7	5	5	2	4	7	3
20	13	6	11	10	4	5	3	2
23	12	6	3	3	3	6	9	3
7	12	6	2	2	4	6	10	4
15	10	5	11	10	5	7	3	4
13	10	5	4	4	1	7	8	1
4	9	4	2	2	2	8	10	2
24	9	4	4	4	1	8	8	0
3	8	4	7	6	3	9	6	3
10	7	3	3	3	1	10	9	1
12	7	3	1	1	2	10	11	1
22	6	3	0	0	3	11	12	1
9	6	3	0	0	3	11	12	1
1	6	3	9	8	6	11	4	7
2	6	3	0	0	3	11	12	1
17	5	2	2	2	0	12	10	2
6	5	2	1	1	1	12	11	1
5	5	2	0	0	2	12	12	0
14	3	1	3	3	1	13	9	4
11	2	1	3	3	2	14	9	5
8	1	0	1	1	0	15	11	4
Sum	213	100	108	100				
Average					2.7			2.3

calculations for structural state transition C dealt with relatively small clearances and overlaps that had to be accomplished around Body 21 and Body 15, among others. The product development team could have judged that the expected variation will have a particularly high influence on relative important functions in this structural state transition.

Table 4. Results of Mode of Action Complexity Scores and high priority tolerance calculation appearance count for structural state transitions

Structural state transition	Mode of Action Complexity Score	Score percentage [%]	High priority appearance count	Count percentage [%]	Absolute percentage point difference	Rank (score)	Rank (count)	Abs. rank difference
A	60	28	14	26	2	1	1	0
D	52	24	10	19	6	2	2	0
E	30	14	6	11	3	3	4	1
C	26	12	10	19	7	4	2	2
F	26	12	8	15	3	4	3	1
B	19	9	5	9	1	5	5	0
Sum	213	100	53	100				
Average					3.4			0.7

6.2. Contributions

The approach described in this paper contributes with the following:

6.2.1. A versatile approach

Due to the nature of the three parameters that contribute to the Mode of Action Complexity Scores, it is possible to review the design from the very first embodiment to the later stages of the product development process, even including the detail design stage. All that is needed is the knowledge about the intended state changes of each body and the expected interactions between the bodies. In contrast, most of the other robustness metrics reviewed in this paper focus on the transfer functions between the design parameters and the functional requirements, which requires a more mature product design and a further understanding of its internal relations.

6.2.2. A bottom-up approach

The Mode of Action Complexity Scores indicate where it is most likely that the variation will accumulate, based only on the description of the intended state changes and the expected interactions. This can be used as an initial approach and an early supplement to other robustness indicators and variation and failure modes analysis approaches that often use a top-down approach and describe how the variation will affect the function. The Mode of Action Complexity Scores may be used for indicating where to start and prioritize the tolerance analysis as well as where to start and prioritize the use of the robustness metrics.

6.2.3. An evaluation approach across structural states

The work presented in this paper builds upon the notion that the variation of the specific geometrical interfaces in the assemblies must be considered in order to evaluate the variation risk, as emphasized by existing literature in modeling variation in mechanical assemblies. As an extension of this notion, this paper contributes with an approach for evaluating the mechanical assembly across the structural states. This evaluation should be valuable for designers since products may have multiple structural states and it is relevant to be able to identify the configuration of interfaces that are particularly prone to variation.

6.2.4. A unifying approach

When collecting the high priority tolerance calculations, we found that the priority lists had been developed in different documents for the different parts of the product and different product development team units. We see an advantage of being able to quickly produce a common list of high priority bodies and structural state transitions, which can be used to improve the coordination of the product development team.

6.2.5. A systematic approach

The process guides the practitioner through the analysis and provides a systematic way of scoring each part and each structural state transition based on countable parameters. This scoring is intended to act as input for the prioritization of the variation risk assessment, including the focus and setup of the later CAT analysis.

The Mode of Action Complexity Scores relate the numerical and relational complexity to the combinatorial complexity or solvability of the system (cf. Suh 2005; Summers & Shah 2010). Counting the interactions between the bodies corresponds to the relational complexity or couplings of the system, (cf. Weber 2005; Summers & Shah 2010), while summing the scores for all bodies for each structural state transition corresponds to the numerical complexity or size of the system, (cf. Weber 2005; Summers & Shah 2010). Assuming an increased accumulation of variation in the mode of action of the parts and structural state transitions that have the highest count, thus experiencing the most, the scores are related to the time-dependent complexity or solvability of the system, (cf. Suh 2005; Summers & Shah 2010).

6.3. Future work

6.3.1. Expanding applicability of approach

The approach presented in this paper addresses mechanical products, and this is also how the case study would be categorized. This perspective is due to the chosen interpretations of what interfaces, interactions, and state changes are in the context of mechanical products and includes the influence of geometrical variation on these aspects. Further work should be done to explore the interpretation of the Mode of Action Complexity Scores in electromechanical and other product categories. We believe that this approach could be beneficial in other contexts also.

6.3.2. Accumulation of variation

In the presented approach, the Mode of Action Complexity Scores B_i and T_j are representations of how many events happen in the mode of action related to the bodies and to the structural state transitions. A topic for further work would include an investigation of how the variation accumulates for higher scores and whether it is possible to estimate the impact of variation solely on the background of Mode of Action Complexity Scores. This would entail either simulations or experiments with a wide range of product designs.

6.3.3. Application for complex products

The approach presented in this paper is derived from the function reasoning and mode of action description by Andreasen *et al.* (2015), and the bodies of the product are here interpreted as the individual parts for the application on the case study. However, for larger assemblies with many parts, it will be an advantage to interpret the sub-assemblies of the product as the bodies. This will reduce the number of bodies to keep track of when evaluating the mode of action complexity.

6.3.4. Integration with CAD tools

The approach could also be implemented in CAD software when the design is mature enough that it has been modeled digitally. This would require the designer to define the structural states and the positions of the parts included in order to ‘translate’ the mode of action into the digital system. However, the CAD tool might contribute with automatic detection of the interactions between bodies and inclusion of statistical process control data from possible already existing production. The CAD tool must count the parameters given in Section 4 and calculate the Mode of Action Complexity Scores. The potential simulation of the geometrical variation according to production data in a CAD tool could be used for comparing the intended interactions and state changes with simulated interactions and state changes.

The approach presented in this paper offers a systematic concept screening method for prioritizing the subsequent tolerance analysis. However, the method requires knowledge about the mode of action of the design as well as knowledge about the expected geometrical variation due to the manufacturing methods and materials used. Integrating the approach in CAD tools would allow a more detailed view of the expected geometrical variation of the parts. Still, the designer must have knowledge about the mode of action of the design.

6.3.5. Comparison of different concepts

Further work could also focus on using the Mode of Action Complexity Scores for comparison of design concepts. The work could include a total score C, which would be the sum of the scores given:

$$\sum_{j=1}^{m} T_j = \sum_{i=1}^{n} B_i = C. \tag{6}$$

For this case study, the total Mode of Action Complexity Score is $C = 213$, as seen in Tables 3 and 4. This score would then be compared with the score of other competing designs. The design with the lowest score would give the product development team an indication of which design has the lowest mode of action complexity. Work regarding this would include normalizing the scores with regard to concept maturity.

6.3.6. Further considerations when using the approach

As described, the results of this study coincided well with results of the tolerance expert and mechanical design team. The subsequent variation risk assessment (including the actual tolerance analysis) must include the evaluation of the following aspects in order to compensate for the sources of errors identified for this approach:

(i) Importance of the function or severity of failure. Do the bodies or structural state transitions contribute to a particularly important function?
(ii) Relative variation size. Do the bodies or structural state transitions require relatively fine motion, small clearances, or overlaps compared to the rest of the mechanical product?
(iii) Reference frame component. Does the frame component have particularly important interfaces?

The presented case study and results only give an indication of the applicability and usefulness of the approach. Further studies are necessary in order to validate the approach presented in this paper. However, this initial study shows the relevance of considering the complexity of the mode of action of the mechanical product together with the geometrical variation.

7. Conclusion

The aim of this paper was to identify if the complexity of mode of action of mechanical products can be related to variation risk and robustness issues and, thus, be used to prioritize the tolerance analysis work. This paper contributes with versatile, bottom-up, unifying, and systematic procedure for calculating the Mode of Action Complexity for bodies and structural state transitions for mechanical products, and the procedure has subsequently been implemented in a real industrial case study design by Novo Nordisk A/S, a world-leading insulin injection device manufacturer. Comparing with the appearances of bodies and structural state transitions identified in the high priority tolerance calculation list used in the company for the same product, we show that the presented procedure results in a scoring that establishes good accuracy, with an average percentage point difference of 2.7 for bodies and 3.4 for structural state transitions.

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