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Application of a graphical scheme for representing the mode of action of products for identification of key characteristics

Kristian Bjarklev^a, Tobias Eifler^a, Niels Henrik Mortensen^a, Steven Linnebjerg^b, Martin Ebro^b

^aTechnical University of Denmark, 2800 Kgs. Lyngby, Denmark

^bNovo Nordisk A/S, 3400 Hillerød, Denmark

* Kristian Bjarklev. Tel.: +45 45255645. E-mail address: krbjark@mek.dtu.dk

Abstract

In order to identify where to focus the tolerance analysis during the product development process, it is beneficial to find the key characteristics. However, for highly integrated, multiple-state products, product designers have difficulties in efficiently communicating and tracking the complex mode of action. As a consequence, not all relevant key characteristics are found in the initial screenings. We propose a systematic graphical representation scheme for modelling the mode of action of products, and we apply this scheme on a case example, in order to illustrate its applicability and its usefulness for the identification of key characteristics.

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Keywords: variation management; key characteristics; representation of mode of action

1. Introduction

In manufacturing of mechanical assemblies, variation of the design parameters that appears in production often leads to reduction of the fulfilment of functional requirements. This decreases the quality of the product that the user perceives [1–3]. In Variation Risk Management (VRM) [4] and Robust Design [5], the issues that variation may cause in the final products are handled during the product development process. This potentially reduces the amount of scrap and allows for wider tolerances, reducing the final production cost. The VRM process prescribes identifying the features of the product that are critical for the proper function of the product, and that are prone to varying - the so-called *key characteristics* (KCs). In order to identify the relevant KCs, it is therefore important to understand the behaviour and the mode of action of the concept that delivers the required functions.

A problem that teams, who develop complex multiple-state products, where interfaces shift along the kinematic cycle of the product, face is that the behaviour and the mode of action of the product is often complex and hard to communicate and

understand [6]. Bjarklev, Mortensen & Ebro [6] observed a lack of a systematic scheme for representing the mode of action of multiple-state products in an intuitive manner. The consequence of this issue is that not all KCs are found in the initial screening, i.e. the first round of KC identification, resulting in a less efficient VRM process [6], risking costly late-stage design changes.

In this paper we present a suggestion for a systematic graphical scheme for representing the mode of action of multiple-state products in an intuitive manner and we show the applicability and usefulness of this on a case example.

Our overarching hypothesis is that using this graphical scheme will improve the communication of the mode of action, which will improve the efficiency of identification of KCs of multiple-state moving products.

In Section 2 the theoretical background is presented, describing how the function and structure of a multiple state product relates to each other. Furthermore, we compare current approaches in literature to this. Section 3 describes how we used our graphical scheme. In Section 4 we present the resulting analysis of the mode of action of a glue gun case example. In Section 5 we discuss how well our suggested

approach is suited for representing the elements of the mode of action and the behaviour of the product, and finally, we conclude in Section 6.

2. Theoretical Background

The process of functional decomposition of the Integrated Tolerancing Process [7] prescribes a decomposition of the functions and behaviour of the product and link the specific geometry (and the geometrical variation) to this. The approach focuses on the kinematics behaviour on a subassembly-level. We decompose the function and behaviour of multiple-state products further, resulting in Fig. 1, where the product is decomposed to feature-level, the kinematics are decomposed to link-level and the behaviour, which consists of state changes and structural state transitions in the product, is further decomposed into the mode of action, which is the external effects and interactions between the bodies (parts) in the product, based on natural phenomena. This view is inspired by function reasoning and kinematic terms [8,9].

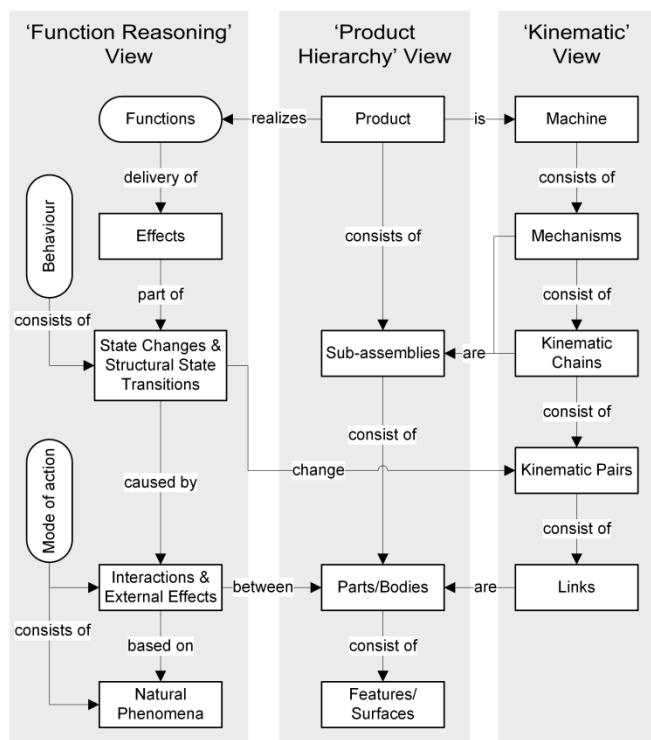


Fig. 1. Decomposition of the Product, Functions, Behaviour and Mode of action, based on descriptions from function reasoning and kinematic terms [8,9].

There are a number of modelling approaches in literature for variation risk management that focus on static subassemblies and the parts in the kinematic pairs and chains, e.g. [10,11]. These do often not consider the multiple states and shifting interfaces between parts of the product and do not explain the product transitions from one structural state to another. We define a structural state as the specific setup of connecting interfaces between parts (kinematic pairs) in a product at a given instance, inspired by [8].

Other approaches (for collaboration between stakeholders and cataloguing design solutions) often map the functions and behaviour of the product on a high level perspective, e.g. [12–15], and they do therefore not include the specific interfaces between parts. This makes it difficult to trace the impact of e.g. surface variations in the product.

Other approaches decompose the functions of the product and locates the relevant variation of the features related to the fulfilment of these functions, e.g. [16–19], but these approaches do also not distinguish between structural states, and do not focus much on the shifting interfaces between parts along the kinematic cycle of the product. Besides, they do not offer a graphical tool for efficiently communicating and documenting the mode of action of these mechanisms.

Our approach focuses on mapping the relation between the interactions and external effects, the parts/bodies, the features/surfaces, and natural phenomena, i.e. the elements that constitute the mode of action, and offering a graphical toolset with the purpose of being able to illustrate the mode of action across the different structural states, including the shifting interfaces between parts, in an intuitive manner. The approach is intended to be used on multiple-state, purely mechanical products and mechanisms, where the parts may interface with each other differently across the different structural states. Thus, the approach is intended to illustrate how the product transitions from one structural state to the next, including the impact of the variation of specific surfaces, forces and movements.

3. Method

The graphical scheme is based on the Variations Effects and Aspects of Mode of Action (VEAMoA) model [20] that describes four aspects of the mode of action of moving products:

1. Transfer of forces. Energy is transferred from part to part as forces acting through surface contact.
2. Movement, placement and deformation of parts, caused by the forces.
3. Positioning of surfaces, including gaps and overlaps, and surface contact between parts. These are setup by the parts.
4. Transfer of information. Information to the user is typically transmitted as the relative position or movement between surfaces.

These aspects create a cycle that together is the mode of action of the product.

The VEAMoA model is intended for binding together and describing the feature/surfaces, parts/bodies, interactions and effects, and the natural phenomena that exist in purely mechanical products, and clarifying how the changing interfaces between parts plays a role in the product function.















Variation may be introduced in any of the aspects, and may propagate through the cycle, affecting the mode of action on various aspects. Considering this helps in finding the KCs, since the designer is prompted to consider the impact of the variation on a detailed level on the mode of action, and ultimately on the function.

3.1. Symbols for representing mode of action

A range of symbols were selected for representing these aspects graphically. The graphic representation enables a more intuitive communication of the mode of action compared to a verbal or written description.

In this paper, we elaborate on this range of symbols, in order to improve the applicability of the graphical scheme for a larger range of products. Table 1 presents symbols for various phenomena for each of the aspects of mode of action.

Table 1. Symbols for representing aspects of mode of action.

Aspect	Phenomenon	Symbol
Transfer of Forces	Driving Forces	
	Nesting Forces	
Movement, Placement, and Deformation of Parts	Continued Displacement	
	Stopped Displacement	
	Rotation/Orientation	
	Internal Energy/Deformation	
	No Displacement	
Position of Surfaces	Overlap or Clearance (Linear)	
	Surface Contact	
	Surface Distance	
	Overlap or Clearance (Angular)	
Transfer of Information	Tactile Information	
	Visual Information	
	Audible Information	

Transfers of forces are represented with square arrows in blue and white. Movements and placements of parts are illustrated with a dot and line arrow, representing the origin of the body and the displacement. For rotation, a circular arrow illustrates the direction of rotation around a specific axis. Internal energies are caused by deformation of the parts, and are illustrated with a lightning symbol. Important linear and angular overlaps, clearances or contacts between certain surfaces are illustrated by a triangle symbol and a circle symbol, respectively. Other surface distances can be represented by a black line. Tactile, visual and audible

information is represented by a hand symbol, an eye symbol and a speaker symbol, respectively.

3.2. Approach for mapping VEAMoA

The approach used for mapping the aspects of the mode of action is as follows:

1. Determining the structural states: In this step, the important structural states of the product are identified. These are the states that the product has to go through in order to perform the intended functions. For the mapping process, the structural states of the product are identified and presented graphically. Typically an entire kinematic cycle is represented.
2. Mapping the aspects of mode of action: In this step, the action conditions necessary for the product to transition to the next structural state are mapped. The conditions are part of the mode of action. The mode of action is mapped in the following aspects: First, the sources of force are identified, and the forces in the system are mapped, distinguishing between driving forces that move or deform the parts and nesting forces that immobilize the parts. Then, the resulting movements, placements and deformations of the parts are mapped and illustrated. The movement is distinguished between stopped movement (movement that is stopped at the given structural state) and continuous movement (that continues after the given structural state). Next, the relative surface positions relevant for the proper force transfer setup are identified and mapped. We distinguish between clearances, overlaps, and surface contacts, mostly. Finally, the relative surface positions relevant for the proper information transfer are identified and mapped.
3. Considering the impact of variation of each of the aspects of mode of action: In this step, variation is introduced and its effects on the mode of action, and thus on the transition from structural state to structural state are considered. This process links the variation on a feature level to the function of the product. Therefore, the impact of variation of forces, part movements, placements and deformations, surface positions, and information transfers on the rest of the mode of action chain is considered.

4. Application on case example

We use a glue gun as the case product for this project. The glue gun consists of eight major parts, as seen in Fig. 2. The main function of the glue gun is to eject molten glue from the tip according to the push of the trigger. The desired behaviour is for the device to grab the glue stick and push it into the heater element, and then return to an initial position without dragging the glue stick out. We divide the behaviour into five structural states as seen on Fig. 3.

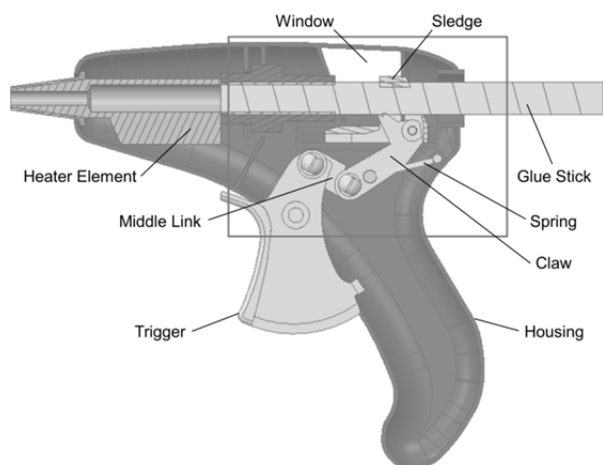


Fig. 2. Cross section view of the glue gun. Figure source [21,22].

4.1. Mapping aspects of mode of action

In the initial state (State A) of the glue gun (see Fig. 3A) the spring provides nesting forces that go through the claw to the sledge into to housing, and from the claw to the middle link, to the trigger to the housing. The parts are immobilized in this structural state. The forces maintain the surface contact between the trigger and the housing and the sledge and the housing. Variation of these surfaces will cause the placement of the parts to be different. The forces from the spring pull the joint between the middle link and the claw upwards, extending the angle between these two parts. Therefore the joint that connects the spring to the claw, must be placed higher than the joint that connects the middle link and the claw, and the spring forces must pull slightly upwards. Finally, the sledge and the claw must allow for entrance of the glue stick.

In the structural state of loading the glue stick into the glue gun (State B, see Fig. 3B) the user exerts forces on the glue stick that pushes it into the opening of the heater element. This positions the surface of the glue stick in a manner that forces are transferred to the claw, which causes a slight rotation and translation of the claw and the sledge, and a rotation of the middle link. The spring is elongated which stores internal energy. In order to successfully transfer to this structural state, the surfaces of the glue stick and the claw must meet, and must do so in a way that the claw moves and causes the internal energy in the spring, which exerts nesting forces, that holds the glue stick in this position.

In the next structural state (State C, see Fig. 3C), where the trigger is pressed by the user, the force that the user exerts on the trigger, rotates the trigger which transfers forces through the joints, extending the angle between the middle link and the claw, which moves the point of attack of the claw onto the glue stick upwards, and transfers forces, that grip and move the glue stick into the heater element. It is again important for the joint between the trigger and the middle link, and the joint between the claw and the spring, to be positioned 'higher' than the joint between the claw and the middle link, so that the angle may be able to widen. It is also crucial both the claw and the sledge make surface contact with the glue stick in

order to transfer the proper forces. The edge of the sledge can be viewed by the user, and its position relative to the housing indicates the how far the glue rod has moved. Finally, the rotation of the trigger must not be impeded by the surfaces of the housing, before the glue stick has been moved the desired distance.

When the trigger is released, the device enters the next structural state (State D, see Fig. 3D). Here, the stored internal energy of the spring is released as forces pulling the claw backwards. Contact between the claw and the glue stick allows friction forces to be transferred between the two. These friction forces rotate the claw, positioning the surfaces of the claw in a manner so that the grip of the glue stick is loosened. A crucial condition for this structural state is that the distance between the claw tip and the sledge is able to increase enough for the grip of the glue stick to release sufficiently, so that the sledge may move backwards without pulling the glue stick backwards. The spring force must be larger than the final friction force. The rotation of the trigger shortens the distance between the trigger and the sledge, which allows the rotation of the middle link, which allows the rotation of the claw.

The final structural state is when the sledge has returned to the starting position again (State E, see Fig. 3E). From here it the device may return to State C. In State E, the forces from the spring have pulled the claw and sledge backwards, rotating and translating the middle link, and rotating the trigger, until surface contact is either made between the trigger and the housing or between the sledge and the housing. In this state, surface contact and force transfer between the claw and the glue stick is relevant in order to hold the glue stick in place. This surface contact and following force transfer is created by the spring, which pulls the joint between the middle link and the claw upwards, causing a rotation of the claw.

4.2. Impact of variation of aspects of mode of action

The abovementioned mapping of the aspects of mode of action results in a list of features that are relevant for the transition from state to state, and thus for the function:

- Placement of joints of the spring and of the middle link: The joint that connects the middle link to the claw part must always be below the neighbouring joints, in order to allow the mechanism to 'stretch out' at certain times, in a manner that causes the claw to press against the glue stick.
- Friction between the claw and the glue stick, and the glue stick and the heater element: The friction between the glue stick and its surrounding parts must be adequate to allow a proper grip at certain states, and a proper slide of the claw at State D. The molten glue in the heater should not be retracted backwards.
- The spring force must be strong enough to overcome the friction forces in the mechanism especially those between the claw and the glue stick, in order to properly retract the mechanism to State E. At the same time the spring force should not become an obstacle for the user, when pressing the trigger in State C.

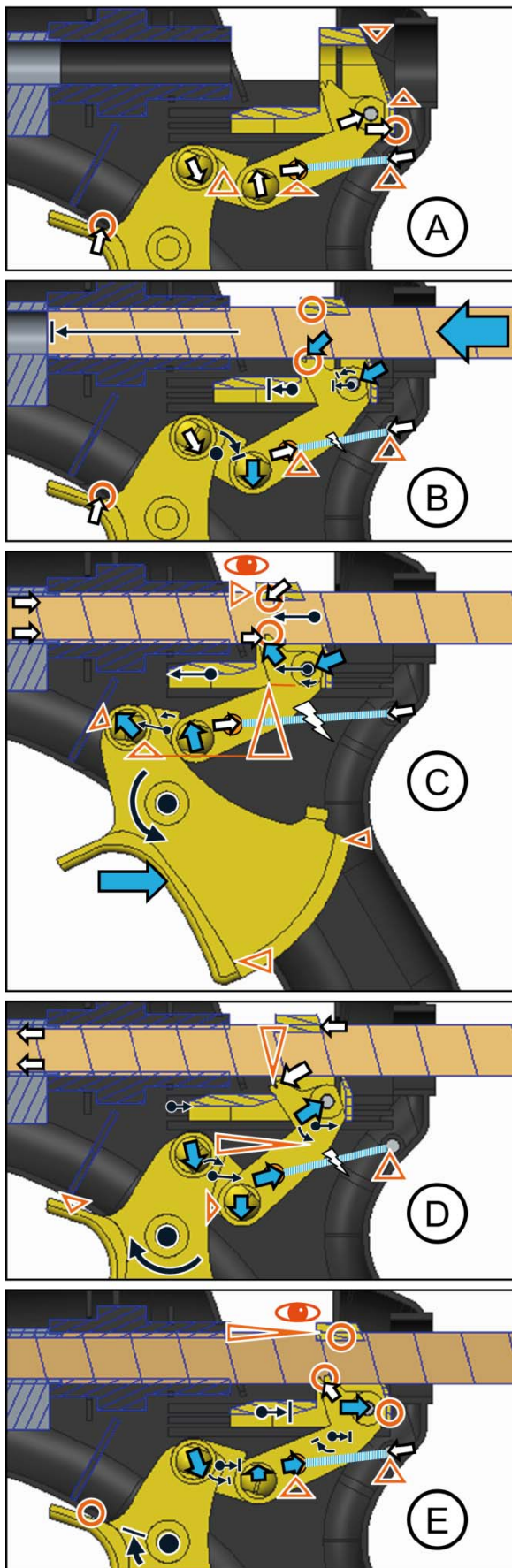


Fig. 3. Mapping of mode of action on structural states of a glue gun. (A) Free state, prior loading of glue stick; (B) Loading glue stick; (C) Pressing trigger; (D) Releasing trigger; (E) Sledge back in start position. Figure source [21].

- Diameter of the glue stick and length of tip of claw: These parameters must allow for the glue stick to enter the device without problems (State B), but also allow for a proper grip of the glue stick (State C).
- Clearances around the trigger: The trigger moves considerably during the kinematic cycle of the mechanism, and must therefore be free to rotate sufficiently to drive the mechanism as intended. E.g., a clearance should be maintained between the surface in the inner part of the housing and the top of the trigger part in State C, so that the glue stick may be pushed sufficiently forward.

If these function-critical features vary considerably then they will qualify as KCs. In the case of a development process, the designers should investigate the variation of these function-critical features further, in order to fully establish them as KCs. The designers will also, to some extent, have experience of how much variation each parameter would be expected to vary. This experience will contribute to a preliminary assessment.

5. Discussion

The VEAMoA approach applied in this paper illustrates the interactions and external effects by mapping the natural phenomena as force transfer and part movement, deformation, and immobilization, and surface position. The VEAMoA offers a new approach for mapping the mode of action of moving mechanisms with shifting interfaces across the different structural states of the kinematic cycle.

Compared to the approach of mapping the joints of the static assemblies of [10,11], the VEAMoA approach offers a more detailed description of the forces that cause the shifts of interfaces, and depicting the parts of the concept allows for a more detailed overview of positions of surfaces relative to each other. However, the visual mapping is relatively more complex due to this extra information.

Compared to mapping of functions and behaviours as in [12–15] the VEAMoA approach maps and manages the mode of action of the product on a part and surface level, resulting in a detailed view of the product. This is beneficial for visualizing the immediate effects of variation. The VEAMoA approach similarly requires a clarification of the functions of the product, in order to map the right details.

Compared to the variation flowdown approaches of [16–19] the VEAMoA approach focuses more on the shifts between structural states in mechanical products. These shifts are crucial for the performance of the products. In future work this focus may be combined with the flowdown format, which offers a clear overview.

Mapping all main structural states of the product will help the designer to create an overview of the different requirements for each of the states and manage how the variation of specific parameters influences the different states.

By illustrating the information transfer in the approach, the detailed view of mode of action is related to the required information function of the device.

Surveying such a simple example as the glue gun would probably be manageable even without structured support, but for more complex devices, the designer may quickly lose the overview of how the parts interact with each other at different points of time. It is in these cases that the support described in this paper will be useful and beneficial.

The symbols developed and presented here create an overview of the mode of action of the product, but must be evaluated by the designer in order to make the final step in finding the KCs. It is necessary that the designer has knowledge about the extent of variation that is expected in the product, particularly stemming from the different manufacturing processes. With this knowledge, it is the purpose of the approach to assist in the evaluation of the consequences of the variation on the mode of action and ultimately on the function of the product.

Future work would include further testing of the VEAMoA approach, e.g. in industrial case studies. This will help to further optimize the approach, so that it may be implemented in an industrial context.

Future work could also include information about the probability of variation of the aspects of mode of action, particularly information about surface variation expected from production. Including this type of information, would likely be easier if the VEAMoA approach is developed into a software-based tool, e.g. linking it with CAD software. Joining the criticality of the interfaces and the probability of variation is a major task in finding the KCs of the product.

6. Conclusion

This paper contributes with a proposed range of symbols for illustrating and mapping the mode of action of multiple-state mechanical devices, with shifting interfaces between parts. The range of symbols has been successfully applied on the case example of the glue gun. Illustrating the mode of action across the different structural states raises awareness of shifting interfaces between parts, illustrates how the product transitions from one structural state to the next, and is useful for supporting the identification of the features that are repeatedly relevant for the mechanism to transition through its kinematic cycle, and can be used identifying the KCs when the designer using the tool has a pre-existing knowledge about the expected variation.

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