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NEW INSIGHTS ON THE CONTACT&CHANNEL-APPROACH – MODELLING OF SYSTEMS WITH SEVERAL LOGICAL STATES

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1. Introduction

In engineering design methodology the product development process is often considered as a process of solving problems [Pahl 2003 and Hubka 1996] and the creation of something new. Problems could arrive from a need of the market that is not yet supplied or from requirements on a product that are not yet fulfilled. Thus, according to [Pahl 2003], [Hubka 1996], problem solving is the central task in engineering design. In order to solve a problem and to develop a new innovative product the design engineer has to translate the required functions into the product's embodiment.
During the product development process methods play an important role in supporting the designer to create products of higher quality in shorter time durations. Additionally, methods help to reduce the numbers of mistakes by checking if the developed embodiment of the product really fits to the intended requirements and functions in an appropriate way.
New products get more and more complex. In order to handle the complexity and to be able to validate the product, there is a need of methods which describe the connection between functions and embodiment. [Sue 1998] describes in the axiomatic design theory the relationship between functional requirements and design parameters. According to the theory, the design process is a zig-zagging progress between the modeling of functions and embodiment in which dependencies arise between the functional requirements and the design parameters of a technical system. With the F-B-S-approach [Gero 2002] as well underlines that dependencies exist between the description of functions and the description of the embodiment of a technical system. Both approaches describe the solving of design problems but only theoretical without giving a hint how to build a suchlike model. The core of a design engineer's work is to translate functions into embodiment. However, this work is not yet supported sufficiently while actually translate functions into embodiment, during the synthesis. This is where the Contact&Channel-Approach supports the designer.
The main requirement in order to be able to synthesize a new product is a preceding analysis [Matthiesen 2011]. Matthiesen states that the synthesis, the creation of something new, is always based on something the designer had seen before, building analogy. And while synthesizing the design engineers analyze their pre-thought solution of the problem and compare it to the intended functions.
All these iterative loops of analysis and synthesis are loops of validation in order to determine the conformity of the designed product to the requirements and need of the customer. According to [Albers 2011] validation is the central activity in product development and in the past has been disregarded in research on product engineering. It should not only be carried out for the final design of developed product, but continuously during the product development process. Thus, the increasing importance of validation in research also refers to the need for support of design engineer during the phase of turning functions into embodiment.

At the IPEK – Institute for Product Engineering, part of the Karlsruhe Institute of Technology KIT, the Contact&Channel-Approach is developed which helps the engineer to assign functions and embodiment of a product and thus, supports the iterative loops of analysis and synthesis with building models while creating a new product. This paper gives a new insight of the approach on how to model systems with several logical states.
After giving an introduction on the Contact&Channel-Approach and its basic principles, the paper goes into detail for the fractal character and the temporal decomposition of systems. Then, the decomposition into logical states by means of the Contact&Channel-Approach is defined in general, before it is illustrated on an industrial example. The validation of a product during the concept phase on its functionality in every possible state of application is presented.

2. The contact&channel-approach – C&C²-A

Conventionally, the main result of the phase of modeling principle solutions and embodiment is the documentation of the product's embodiment with all shapes, tolerances, material etc. Mostly, functions are also documented, often in terms of a function structure. Both documentations are helpful and needed for furthers steps during the development process. However, it is not sufficient to only keep records of functions and separately record the embodiment design. It is also essential to link both issues, so that a connection between functions and the fulfilling embodiment is drawn. But not only documentation is important and necessary. The assignment of functions to embodiment supports the design engineer by validating his result of the design process, a function-fulfilling embodiment of a product.
Due to an increasing complexity of products and single technical parts having a stake in more that one function, it is necessary to manage the assignment of functions and embodiment on a more detailed level than the level of engineering parts. In order to be able to link functions and non-component based structures of a product, the Contact&Channel-Approach (C&C²-A) is developed at the IPEK – Institute of Product Engineering. By using the basic elements Working Surface Pairs (WSP) and Channel and Support Structures (CSS) as least common elements it is possible to open up the common product structure which is conventionally grouped into systems and sub-systems.
The approach was first introduced in 2002, when it was called Element Model "Working Surface Pairs & Channel and Support Structures" [Matthiesen 2002]. With continuous further theoretical development as well as validation in several case studies of industrial applications, e.g. in [Albers et al. 2008], the approach has reached its today's status.
The approach supports the design engineer while analyzing and synthesizing of products during his or her daily work which means not necessarily working in a team but also to work alone and to pre-think products which fulfill the desired function, e.g. designing the actual parts. Pre-thinking means to imagine and figure how a system can be realized. With the basic elements and hypotheses of the approach the engineer is able to draw a connection between functions and the designed embodiment.

2.1 Basic principles of C&C²-A

The approach is based on the idea of designing interfaces (contacts) through structural elements, the Working Surface Pairs, and structures which are able to channel, the Channel and Support Structures, which transfer matter, energy or information from one interface to another. It goes back to earlier considerations of design scientists like, e.g., Rodenacker, Roth, Hubka and others but adds definitions concerning the relations between the basic elements of different technical systems. It is applicable for every technical system which interacts with its environment and meanwhile fulfills its function.
The relation of functions and the embodiment is drawn up by the usage of the basic elements of the approach. The elements can be assigned to functions as well as shapes and structure of a product. By means of the assignment it is possible to describe effects and functions of a product related to the embodiment. Three hypotheses represent the rules for a consistent Contact&Channel-Model (C&C²-M). The C&C²-Approach defines all elements and hypotheses whereas the C&C²-Model is built by use of the approach and is a model of a technical system with a defined scope of model building.

2.1.1 Basic elements and hypothesis

One basis element is the Working Surface (WS). These surfaces interact permanently or occasionally with another surface and contribute to the transfer of matter, energy or information in the system. Two interacting WS build a Working Surface Pair (WSP). WSPs can be found inside technical systems, e.g. at the contact surface of interacting components, but they also represent the interfaces to the environment.

Channel and Support Structures (CSS) are volumes of matter, liquids, gases or spaces containing fields, which connect two WSPs. They enable the transfer of the matter, energy and information from one WSP to the other and are also able to store the system variables.

Further elements of the approach, e.g. Limiting Surfaces (LS) and Remaining Structures (RS), are defined in [Matthiesen 2002].

In [Alink 2010] a new element, the Connector (C), is introduced which underlines the integration of the system into its environment. Connectors are virtual elements which represent and comprise all influences, parameters, constraints and their linking on the working surfaces at the system boundary which seem to be relevant for the given task from the model builder's point of view. Thus, the connectors are relevant, reduced representation of the environment for the description of the observed function. Specifying the right properties of the connector, identifying the relevant environmental parameters, is essential for the building of an adequate model. Systems can only fulfill its function when embedding into the overall system. The connector itself is not part of the area of design and creativity for the design engineer but defines the boundaries of this area.

With three hypotheses C&C²-A is defined unambiguously. The first hypothesis states that every technical system fulfills its function by interacting with adjacent systems. Effects can only take place if a WS is in contact with a further WS and thus a WSP is build up.

How functions can be modeled is defined in the second hypothesis. Functions are represented by at least two WSPs, the connecting CSS and at least two Connectors which embed the model into the environment. The properties of WSPs, CSSs, Connectors and the effects taking place in the WSPs and CSSs are determining for the fulfillment of the function.

The third hypothesis defines the adaptable character of the approach according to the focus of observation. Thus, every system and subsystem can be described by the basic elements WSP, CSS und Connectors on different levels of abstraction and detail.

With the C&C²-Approach it is now possible to describe functions and effects in relation to the fulfilling product embodiment. Functions and effects are defined differently in literature. In the C&C²-Approach effects occur inside WSPs and are related to shapes and geometries of a product. As the second hypothesis states, a function can only be fulfilled if the system is embedded into the environment. Likewise, an effect can only occur integrated in the overall system. The properties of a WSP define the specifications of the realized effect. Physical or other principles, which are free from any kind of shape, geometry or matter, are utilized in WSPs or CSSs to creating effects. A diagram of an effect and of a function in terms of C&C²-A is shown in Figure 1.

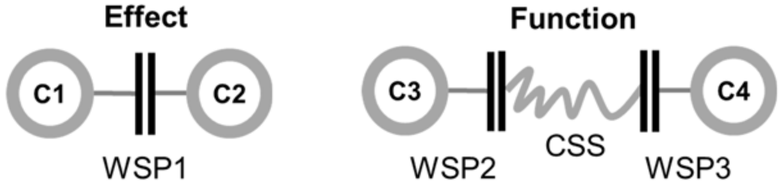

Figure 1. Effect and functions in terms of the C&C²-Approach

2.1.2 The fractal character of C&C²-A and temporal decomposition of design problems

In order to reduce the complexity, design problems can be split up into smaller pieces due to the fractal character of the C&C²-Approach. It is presented in [Albers et al. 2008]. Usually in a technical system there is not only one relevant place of function accomplishment, which has to be determined in detail, but several of them. Relevant places can be WSPs and CSSs within the system boundary, which should be observed in detail. The zoom at the different locations can be adapted according to the complexity of the single location and according to the problem at hand. For a complete recording of the problem every relevant place for the function fulfillment has to be analyzed at a higher level of detail. This is possible due to the fractal character of C&C²-A, which is enabled by the third hypothesis.

The process of zooming in and zooming out is called the Comb Approach [Albers et al. 2008]. While zooming into a relevant place or switching to a less detailed view on the system, the boundary of the system to be designed is set new view and thus, new Connectors have to be defined.

The fractal character allows a decomposition of the design problem on different levels of detail but at only one certain point of time. In the majority of cases, not all functions of a product are fulfilled at the same time. The functions can be fulfilled in temporal states, e.g. a jigsaw which repeatingly pulls up and presses down the saw blade. In order to manage the complexity of those design problems they can be decomposed into different states [Albers et al. 2008]. The resulting model is called sequence model. An example of a sequence model is shown in Figure 2.

Sequences are certain sets of WSPs and CSSs. Within each state different sequences can be observed and several functions can be fulfilled. Several functions can be fulfilled parallel within a state and functions can also exist within several states. During one state functions and effects are the same and do not change. WSPs and CSSs are the same. When a WSP dissolves or a further WSP and thus a further function occurs or changes, the state ends and the next state follows.

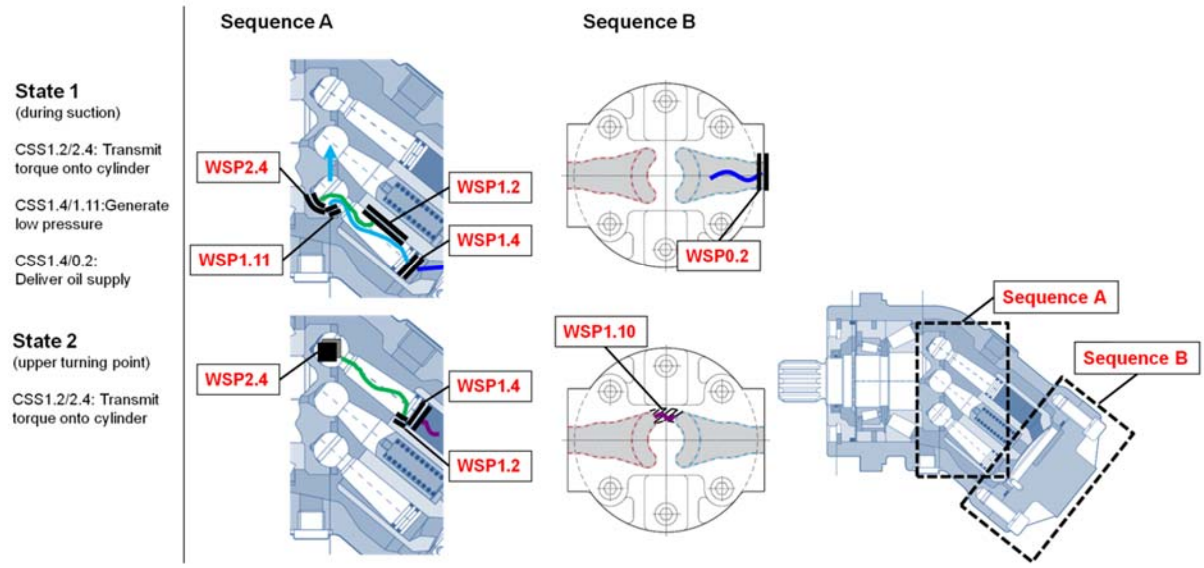

Figure 2. Extract from a sequence model of an axial piston pump

A sequence consists of at least two states. It is described for a special system boundary and respectively for one relevant location. With enlarging the system boundary more sequences can be considered which can affect each other. All interactions and influences between the different sequences have to be defined.

Both the fractal character of the Contact&Channel-Approach and the possibility of a temporal decomposition of the system at hand by means of the sequence model help the design engineer to manage the complexity of the design problem.

2.2 Decomposition of logical states with C&C²-A

With the possibility to decompose technical problems into temporal sequences a great number of systems can be modeled. But there are still systems which do not possess a chronology of states. A state is defined when the variables take a constant value. Thus, states can also occur according to a logical order and they can influence each other. Examples would be safety mechanisms like unlocking devices which have to be activated before the actual function of the system can be fulfilled.

The complexity of those systems is not easy to handle for the design engineers. Especially for observations of the system's functionality and for the search for possible errors, e.g. FMEA, the complete system has to be examined for every single state and the different combinations of states. This proceeding is extremely time-consuming and cost-intensive. Most present methods and the present Contact&Channel-Approach concentrate on static systems or dynamic systems with defined chronologies. Thus, a clear modeling of logical states would support the design engineer.
Definitions of the temporal decomposition and the fractal character can be reused for the preparation of a logical structure. The fractal character has to be utilized in order to observe various locations with different focuses. Sequent states as in the temporal decomposition do also occur in systems with logical states. There are also states which directly influence each other, so that a state automatically follows another state. Within systems that offer different logical states, WSPs and CSSs are dissolving or occurring and thus, several functions are fulfilled during different states.
In order to decompose the system and build up a logical structure the following steps support the design engineer with little experience in describing systems with several logical states. The recommended steps were developed out of experience in analyzing with the C&C²-Approach. The instructions were validated in industrial projects as the in chapter 3 described project. As every analysis with C&C²-A, the relevant parts of the system and its borders have to be defined, before generating a C&C²-Model.

2.2.1 Detection of the relevant WSPs which are mandatory for fulfilling the main function

In order to decompose a technical system it has to be analyzed for (assumed) important points. Important points are WSPs which are relevant or mandatory for the fulfillment of the main function. Especially WSs, which temporarily build WSPs and hence contribute to the main function, have to be analyzed. The contact of those WSs, building WSPs, enable the transfer of matter, energy of information and are often mandatory for other WSPs to be build. Dissolving WSPs can cause the building of WSPs at another location. With an upcoming WSP also a new CSS originates and a new function can be fulfilled.

2.2.2 Identification and clustering of the CSSs which contribute to the building of a WSP

CSSs have to be defined, which contribute to build a temporal existing WSP. Often more than one CSS are involved in providing a new WSP by connecting two WSs. This step needs to be executed on a high level of detail. However, not every part and subpart of the system should be observed but only the relevant locations detected in first step and their surroundings. This corresponds to the fractal character and the comb approach of [Albers et al. 2008].
In addition to existing CSS also possible CSS have to be identified, which only exist if a temporal WSP is built. It needs to be observed which CSSs contribute to building the WSP. All CSSs which fulfill the criteria can be clustered to a superior CSS.

2.2.3 Identification of several logical states of the CSS-cluster

Logical states of the superior CSSs, the CSS-clusters, have to be identified. For the case that a new WSP occurs, a new connecting CSS arises which fulfills other functions as for the case that a WSP and thus the connected CSS dissolve and a function goes missing. Those different states of the clusters have to be determined. Possible for recording the states is the formulation of different functions which are fulfilled during the different states. Alternatively only one function can be defined for the CSS-cluster which is enabled for one state and disabled for the other state. The cluster than can be called "switch" with the states "on" and "off".

2.2.4 Arranging of a logical structure for representing all correlations and dependencies between the CSS-clusters.

For having an overview on all CSS-clusters and their different states, a logical structure must be arranged. All relevant dependencies and correlations between the clusters have to be defined. WSP which are not permanently existent build the interfaces between the CSS-clusters and to the environment of the system. With dissolving or building of a WSP within the system, the states of at least two CSS-clusters are affected. A changing state of one CSS-cluster thus can cause the change of the adjacent cluster. A state of a cluster can also be influenced by interaction with the environment, e.g. a user. The impact from the outside of the system, represented by the connector, is transmitted by the WSP at the system boundary into the system. Dependent on the correlations of the CSS-clusters and the logical structure an impact from the outside can cause a series of reaction inside the system and also an impact on the environment at another interface, on another connector. A clearly arranged logical structure of all CSS-clusters represents all dependencies and correlations. Hence, it is possible to identify all different states of the overall system.

3. Application of the logical decomposition in an industrial project

For research on the decomposition of logical state by help of the Contact&Channel-Approach a project in cooperation with the power tool producing company was conducted. The functionality and reliability of a new innovation had to be proven for every possible case of application and misapplication by the user. The observation had been conducted during the stage of conceptual design in order to ensure the reliability during the early stages of the development process. The determined power-tool has the main function ‘easy nailing of metal sheets onto concrete without predrilling’. The power-tool is similar to the tool shown in Figure 3 with more than 200 parts and even more functions that are fulfilled. The task concentrated on the observation of the mechanical parts of the trigger mechanism. A row of levers have to be moved in a particular order to release a nail and not to endanger the operator. The safety requirements on direct fastening tools are extremely high and fundamental for the protection of the tool user during the application.

Figure 3. Power-tool with over 500 functions realized in the embodiment [Matthiesen 2011]

In order to ensure the safety of the power tool the functionality of the trigger mechanism with all its safety features at any point in time the engineering design team started to solve the given task by using the failure mode and effects analysis with a bottom-up strategy. As preparation the team broke the function structure down to the level of single parts. The structure ended in a huge dimension and the FMEA thus turned out to be inefficient for the given task. Too many single parts and particularly the high number of functions and interactions between the parts of the technical system at hand caused an unmanageable matrix and frustration of the design team. The overview and the consequence for the functionality and reliability of the overall system were not possible to generate within the intended time frame. The time factor and thus cost factor forced the team to stop the FMEA and apply a new approach for the validation of the functionality of the product concept.

3.1 Logical decomposition of the problem at hand

The first step of the new approach was to detect all interfaces of the tool to the environment. The interfaces presented the WSPs at the system boundary which only exist if the power tool was in use and the user and application were interacting with the tool. An overview of actions which the user performed and the resulting actions of the power tool helped to create a rough understanding of the

power tool behavior and function. A special order of interactions with the user and with the environment was required in order to fulfill the main function “nailing of metal sheet onto concrete”.
In order to detect the relevant WSs and WSPs for fulfilling the main function, the observation started at the WSP which transmitted the main force to the nail and hence contributes to the function “accelerate the nail”. Based on the detected WSP it was determined which CSSs lead to transfer energy to this WSP. This CSS only exists as long as the two WSPs, which are connected by this CSS, exist. At the moment new WSPs occur new CSSs are relevant. Hence the next two relevant WSPs were found.
After identifying all relevant WSs and WSPs as important interfaces within the system for fulfilling the function, CSSs between the different WSPs were observed. As stated before, several levers were used in the power tool which had to be actuated for fulfilling the main functions. These levers presented the CSSs between the relevant WSPs. But a lever did not always consist of only a single part and a single CSS. Mostly, more than one CSS contributed to the contacting of two WSs to a WSP. Additionally to the actual lever, for example the lever support and a spring, which supported the resetting of the lever, and a CSS as mechanical stop for the lever were also required to fulfill the intended function. The associated CSS were clustered to a superior CSS.
For every superior CSS the logical states were identified. Due to the fact that most clusters had only two different states (fulfilling or not fulfilling the main function) they were called ‘switches’ with the states ‘on’ and ‘off’. Few switches owned more than two states because they contributed to the building of more than one WSP. Figure 4 shows a C&C²-model of switch no. 2. All embodiment-function elements – the elements which directly support the function fulfillment (WSP, CSS and Connector) – are shown in black. Elements in grey only serve for easier comprehension of the illustration. The presented switch is permanently in contact with switch 1 at WSP1.1. For state “off” switch 1 is only interacting as a mechanical stop and the main force is not applied by switch 1 (the reaction of the spring force is not included in this model). This information is recorded in connector C1.1. Thus, for this special purpose of modeling the only input into the system given by C1.1 is information about the lever position. The fulfilled function in state “off” is “*pushing the lever to “off”-position*” realized by WSP1.1, WSP1.2, the connecting CSS1.1/1.2 and the embedding into the environment with the connectors C1.1 and C2. In state “on” the connector which represents all relevant parameters of switch 1 differs from the connector C1.1 in state “off” and thus is named C1.2. Now the main force (which has a greater amount than the spring force) is applied by switch one. This condition is represented by C1.2. The lever has now contact to switch 3 and the new WSP1.3 appears. The fulfilled functions in state “on” are “*Apply counteracting force*” by WSP1.1, WSP1.2, the connecting CSS1.1/1.2 and the connectors C1.2 and C2 and the main function “*Transmit main force to switch 3*” by WSP1.1, WSP1.3, the connecting CSS1.1/1.3 and the connectors C1.2 and C3.

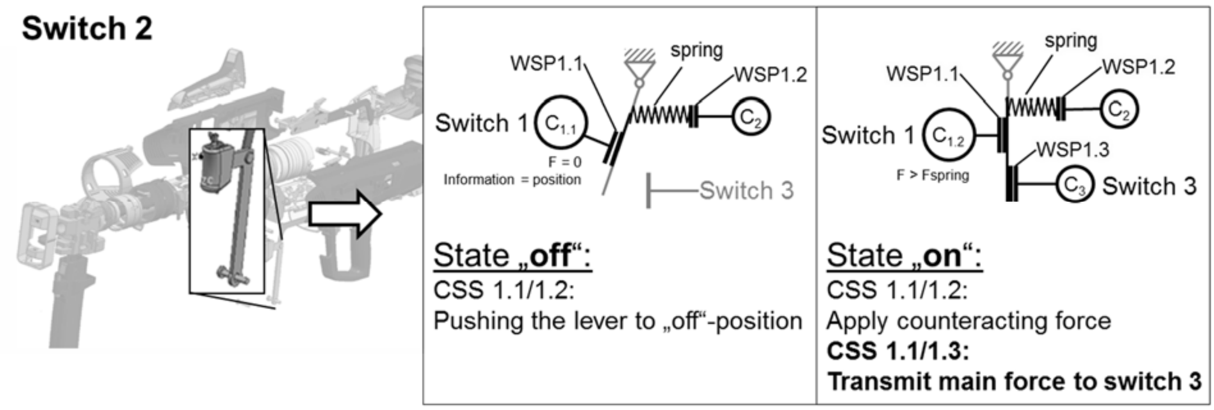

Figure 4. Switch notation of a CSS-cluster

With the switch notation as in Figure 4 the interfaces to the adjacent switches were already defined. The logical structure could be arranged on basis of these interfaces. Switches which directly influenced each other were linked with a bolt. Switches, which had to change their states in a particular order for changing the state of the following switch, were combined with an AND relation. In the resulting logical structure, see Figure 5, the state of switch 6 was only manipulated when first switch 3 changed its state to ‘on’, then switch 4 changed to ‘on’ and at last switch 5 was actuated. Additionally to the CSS-clusters as switches also button, which represent the interface to the connectors, for inducing the change of states were included in the structure. Several sensors were positioned in the power tool for detecting the state of several switches.

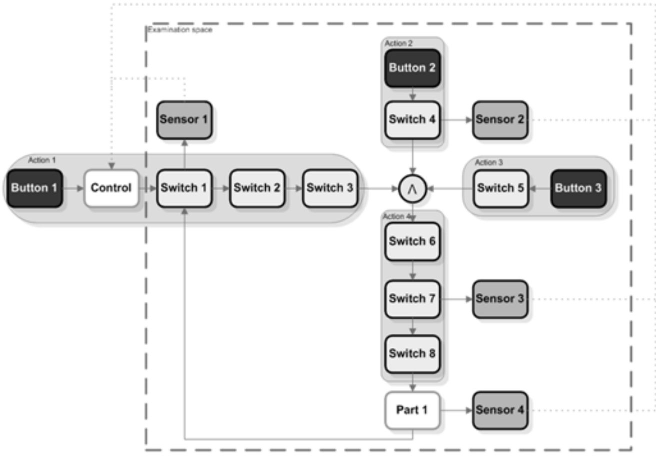

Figure 5. Arranging the logical structure

For the complex tool with more than 200 parts a switch structure with 12 switches were generated which were relevant for the safety of the tool. The structure contained all switches with their different logical states in behind and dependencies and correlations to other switches. Only for the case that all switches reached the ‘on’-state in a certain order the trigger was allowed to release. With the generated logical structure from Figure 5 a concentrated analysis of functionality and reliability was possible.
For the validation of functionality and reliability of the power-tool an adapted FMEA could then be conducted for the technical system. Due to the fact that material failure should not be observed, all interactions with adjacent switches and within the switch were determined on potential failure modes, the consequential potential failure effects and the effect on the whole logical structure, thus on the trigger mechanism. Further potential causes of the failures were detected and measures were set up.
Due to the clustering of CSSs and the identification of the cluster’s states, the arranged logical structure contained only 17 interactions of the switches instead of more than 1000 interactions of the whole power-tool of Figure 3.
For observing potential failure modes especially the WSPs as interfaces between the CSS-cluster and the clusters itself were determined. Particular attention was paid to effects occurring in WSPs. Designed properties of CSSs were also determine with exception of material properties which were excluded from the task.

3.2 Achievements of the logical decomposition with the C&C²-Approach

Due to the two levels of detail generated with the Contact&Channel-Approach the adapted FMEA could be conducted more time-efficiently and well-directed for the given task. Potential failure effects were detected consistently on two levels, the level of the logical structure with CSS-clusters and the detailed level of the CSS-cluster itself. Potential effects on the logical states of the switch as well as effects on the logical structure and thus on the overall system were determined.
The implementation of the logical decomposition with the C&C²-Approach made it possible to observe the whole trigger mechanism for every single state of the overall system and hence eased the search for failure modes. For every switch effects between intended WSP were observed. The impact of unwanted effects, e.g. friction, on the function of the switch presented a potential failure. Another way of detecting potential failure was the search for unwanted WSP. Such WSP could arise e.g. due to poorly chosen tolerances. Additionally WSs which connected and built a WSP at an unwanted state could be found.

Some failure could only be found by observing single CSS-clusters by means of C&C²-Approach. In those cases determined why the function of the switch failed. Either the switch stayed on 'off'-position and thus cause a defect of the whole system, or the switch moved to 'on'-position even if that was not intended. The second case is extremely unsafe due to the possibility of an uncontrollable setting of a nail.
Other measurements for a more reliable power-tool could only be observed on the level of the logical structure. The switches had to be set to 'on'-position in a certain order. In the switch structure, some switches were connected with only two other switches, a preceding and a subsequent switch. Some of them were connected to more that one preceding switch, in the structure combined with an AND relation. For the case of only one preceding and one subsequent switch, the actual switch had to fulfill an additional function for justifying its existence. For the case that the additional function of the switch could also be performed by an adjacent lever, the switch could be left out. Thus, the technical system could be simplified. Switch 2 in Figure 5 was only interacting with the preceding switch 1 and the subsequent switch 3. It owned only one additional function beside the transmission of power flow from switch 1 to switch 3. Hence, the design team considered to integrate the additional function into one of the other switches and leave switch 2 out. Thus, the possibility of failure in switch 2 was eliminated. Those measurements could not be developed without the logical decomposition of the system.

4. Conclusion

The Contact&Channel-Approach supports the design engineer during the analysis and synthesis of technical products. After the development of the temporal decomposition, the presented logical decomposition of systems enlarges the range of application for the C&C²-A. Now, changes in state which do not follow a chronology can also be modeled with C&C²-A. During the presented industrial project the logical decomposition could be validated and led to saving of time and money.
For the observation of the power tool with attention on the functionality and reliability an inadequate focus on the system and disregarding the different logical states during the validation meant an endangerment for the operator due to an uncontrollable setting of a nail. By means of the logical decomposition with C&C²-A and its fractal character, a C&C²-Model with a logical structure was generated on two different levels of detail. The analysis of potential failure modes was conducted on the level of the CSS-clusters and on the level of the logical structure. The determination of the different states of CSS-cluster made it possible to observe potential effects on the single switch as well as on the whole switch structure and thus the whole trigger mechanism.
For the validation of the application of a logical structure further case studies should be conducted, preferable in an industrial environment. Furthermore it is planed to link the logical C&C²-A structure to a propositional logic. For more complex systems with a high number of different states it could be helpful to develop a logic which automatically could check every combination of cluster-states within the system. A fast way of proving the reliability of systems with several logical states could be developed.

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