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C&C²-AFM - An embodiment design- and function-based approach for Analysis of Failure Mechanisms

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Abstract

In this article, the authors present a model-based approach that links the functional with a physical model layer based on the Contact and Channel Approach (C&C²-A), thus enabling an effective and efficient determination and assessment of the failure root causes and consequences. The approach is designed for the scenario where the failure modes are already identified, but the associated failure root causes or consequences as well as their underlying failure mechanisms have not yet been determined or assessed. First, the previous work and the foundations are introduced and discussed. They are then linked to form a procedure model, which should enable the reader to apply the approach to mechanical failure mechanisms in mechatronic systems. The resulting approach has the potential to improve efficiency and effectiveness in the case of complex mechanical failure mechanisms compared to conventional approaches such as Failure Mode Effect Analysis (FMEA) or Fault Tree Analysis (FTA).

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Keywords: Failure Analysis; Failure Mechanism; Root Cause Analysis; Failure Mode and Effect Analysis; Contact and Channel Approach; Embodiment design and function

1. Introduction

An engine induces vibrations to a supported shaft in the neighboring subsystem. There is a technical risk that the bearing will fail because of vibration wear. Such or similar failures, which are based on physical and chemical effects and are locally or temporally separated from the failure effect location, pose a challenge in failure analysis. Especially, if corresponding experience from previous product generations is missing. The challenge here is to understand the underlying failure mechanisms.

Failure mechanisms describe the causal relationships between the failure causes and their effects. These relationships are determined in some approaches on a logical/functional model level (e.g. in the Fault Tree Analysis or Root Cause Analysis) and in other approaches (e.g. in crash simulations) on a detailed chemical/physical model level, considering material, information and energy flows. However, not always are such quantitative models or resources for their development available. In such cases, it is necessary to use qualitative collaborative methods involving experts for identifying, analysing and evaluating these causal relationships. Hereby, the difficulty lies in identifying and assessing such failure mechanisms efficiently and yet as completely as possible that span across multiple system components and interfaces as well as go beyond the system boundaries. Often the energy, information and material flow of these failure mechanisms do not follow any of the paths envisaged by the product developer. If these failure mechanisms are not understood, a false probability rating or counter measure might result, due to the incomplete, incorrect or unknown underlying failure mechanisms. For these reasons, a systematic analysis of failure mechanisms is important for ensuring product quality.

In this article, the authors present a model-based approach that links the functional with a physical model layer based on the Contact and Channel Approach (C&C²-A), thus enabling an effective and efficient determination and assessment of the failure root causes and consequences. Due to its methodological origin, the approach is called C&C²-AFM (Analysis of Failure Mechanisms).

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2. State of the art

2.1. Necessity for model-based approaches in failure analysis

FMEA (Failure Mode Effect Analysis) and its variants, including FMECA (Failure Mode Effect and Criticality Analysis), are widely used in industries such as automotive, medical technology, aerospace and widely approved as failure prevention methods. Studies carried out in recent years have shown that in these industries there are needs for a more precise description of the technical risks [1] as well as for less experience-driven, more formalised failure analyses [2]. Roth and Lindemann [2] derive based on this the necessity for a model-based approach to support the FMEA. However, an extensive state-of-the-art review in which nearly 40 years of published FMEA research and application reports where analysed, shows that regarding failure analysis there is still a "lack of proper models (e.g. Multi-physics) to describe cause and effects chain"[3].

2.2. Review of current model-based approaches

Regarding recent model-based FMEA approaches, several SysML-based [4], [5], CAD/PLM-based [6] and ontology-based [7], [8] FMEA integrations have already been proposed. However, the previous approaches focused primarily on the topics "Reusability of knowledge from failure analysis" and "Increasing efficiency in failure analysis". The effectiveness on the other hand can be increased by considering not only function-induced failures, but also physical (e. g. breakage, creep, etc.) or chemical (e. g. corrosion) induced failures in the root cause analysis [9]. An empirical study, which analysed a further developed Design Review based on Failure Mode (DRBFM) approach and compared it with the conventional approach, showed that the study participants often overlooked complex mechanical cause-effect relationships [9]. This shows that it is necessary to fully consider the underlying failure mechanisms. Due to the lack of consideration in conventional FMEA, a further development approach called Failure Mode, Mechanisms and Effect Analysis (FMMEA) was proposed [10], [11]. Yet, the original FMMEA approach relies primarily on known failure mechanisms (in form of lists) and does not support a systematic derivation of the failure mechanisms. This matter has already been addressed by a previous publication of the authors by combining the FMMEA approach with the Contact and Channel Approach (C&C²-A) [12].

2.3. C&C²-A – Contact, Channel and Connector Approach

Albers and Matthiesen [13] state that a component alone cannot fulfill a function, because functions are the result of interactions between (sub)systems (e. g. components) and (sub)systems. On this level, various system properties such as stiffness of materials, the roughness of surfaces in contact with each other, contribute significantly to the functional fulfillment. Therefore, the connection between the embodiment design and the function of a technical system is the key to its understanding [14]. This is the basis for the Contact and Channel Approach (C&C²-A). Systems and their functions are represented in C&C²-models. These form the so-called "Wirk-Net" [15], which describes the energy, material and information flows using the three C&C²-elements: working surface pairs, channel support structures as well as connectors [15]. These elements are defined as followed:

Working Surface Pairs (WSP) are set up when two arbitrarily shaped surfaces of solid bodies or generalised interfaces of liquids, gases or fields get into contact and are involved in the exchange of energy, substance and / or information. [16] according to [17]
Channel and Support Structures (CSS) are volumes of solid bodies, liquids, gases, or field-permeated spaces that connect exactly two pairs of surfaces and allow the conduction of matter, energy, and / or information between them. [16] according to [17]
Connectors integrate the properties, which are relevant to the effect and are located outside the design area, into the system view. They are an abstraction of the systems environment, which is relevant to the description of the function under consideration. [16] according to [18]

Figure 1 shows a failure mode and its failure mechanisms in an extended C&C²-model [12] for a linear pneumatic actor. To realize the switching movement, the actuator is supported by the engine housing (Connector C2) and varies the position of the shift lever (CSS1) by the linear movement of the piston. The energy required for this is provided by the compressed air system.

With the help of the extended C&C²-model, both inherent failures [19], e. g. failures that are part of the Wirk-Net intended by the product engineer, and non-inherent failures [19], which result from deviating system behavior, can be determined and assigned. The relevant connector(s) are then identified and their influences on the C&C² model elements of the Wirk-Net considered.

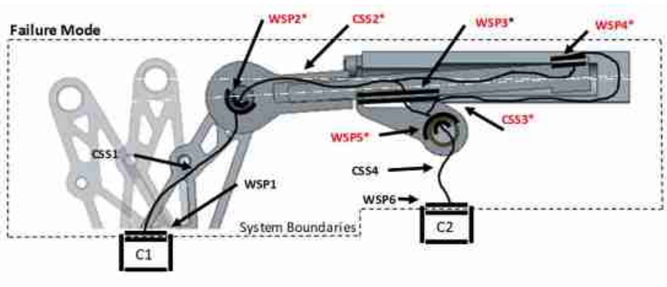

Figure 1: Failure Mode and its failure mechanisms with C&C²-A

The previous publication [12] on this approach dealt mainly with the potentials arising from model-based analysis of failure mechanisms at the level of embodiment design and function. The introduction of a procedural model that supports the application of the approach is still an open issue. This will now be addressed by this article.

3. Research Methodology

Based on retrospective applications of the approach as well as a project-accompanying application, a first empirical study (n1= 38) was designed and conducted to further develop and evaluate the approach [20]. In the first study, the focus was on workshop-based failure analysis in teams based on defined failures. In summary, the empirical results [20] demonstrated that the use of C&C² models in failure analysis has a positive effect on the efficiency as well as the comprehensibility.

Products	Production Systems
Trailer coupling with integrated force measurement (robustness)	Tool wear of a CNC spring coiling machine (robustness)
Split middle armrest for passenger cars (robustness)	Tool wear of a CNC turning machine (robustness)
Gear shift actuation system for a race car (reliability)	Assembly of a gas valve (mountability)
High-pressure fuel pump for passenger cars (reliability)	Series development of an eboard concept vehicle (safety, reliability)

Table 1: Overview of application and evaluation cases for C&C²-AFM

In order to further develop the approach, the approach was applied to various real systems as described in Table 1. For example, the gear shift actuation system for a race car from the example above (Figure 1). To ensure the completeness of the failure mechanisms used, summaries (lists) from the state of the art were used [21]–[23] and these were modified for use with the C&C²-Approach. From the modelling and analysis of these application cases, insights were gained, converted into rules and finally investigated in a second empirical study (n2=42) [24]. The second study [20] was conducted in virtual environment, so that the participants worked on defined failures in moderated teams. This time it proved that the approach also has a positive effect on the scope of the analysis. The test groups had a significantly wider analysis scope compared to the control group, which mainly used fault tree analysis. At the same time, thanks to video recordings of screen transmission, the second study has provided valuable insights into the way in which the study participants determine system influences. For detailed results of both studies, the authors refer to the separate publication [20].

The results also showed that the Wirk-Net is limited to the physical and chemical domain. The fault tree analysis is not tied to a domain, so that one can switch between the system and the process domain within the same failure mechanism analysis. This advantage of the fault tree in the analysis could be used to integrate different domain-specific models. The result could be complex failure mechanisms that span multiple domains and thus several domain-specific models but are summarised for overview-purposes in a single fault tree.

This impulse gained from the second study [20], was the basis and the main driver for this further developed approach, which is presented in the following chapters based on the application case of the gear shift actuation system.

4. Procedure model and application guideline

The approach is an extension of the FMEA, similar to the DRBFM approach developed by Toyota. The core element of C&C²-AFM is the integrated analysis of both embodiment design and function. For this reason, the approach spans across the common FMEA phases “Structure Analysis” and “Functional Analysis” according to AIAG/VDI [24]. In other words, if interfaces and interactions are identified at system structure level, they are always examined in the context of function fulfillment. The approach was developed for the analysis of technical systems and focuses on the mechanical extents of mechatronic systems. With further added models, also other domains can be integrated in the analysis based on C&C²-AFM. The focus of the approach lies in the fourth phase according to AIAG/VDI [24], the “Failure Analysis” phase. Here, the approach supports the identification of failure locations and based on this starting point the systematic determination of the failure root causes and/or consequences. Figure 2 shows the procedure model for the approach. This is divided into three main steps, which in turn are subdivided into three sub steps. The first step is the definition and description of the failure analysis scope. This step ensures that the embodiment design and functional context is prepared for the analysis. Depending on the objective or the preliminary work,

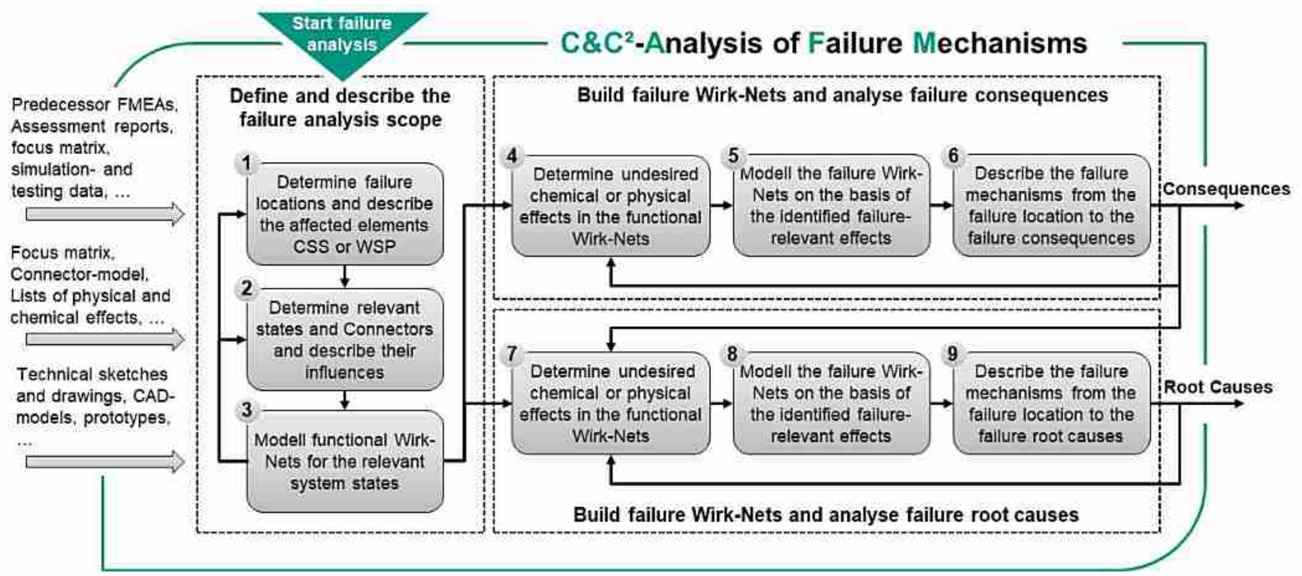

Figure 2: Procedure model for the C&C²-AFM approach

the analysis of failure consequences or the failure root causes represents the next step. In analogy to the FMEA, this sequence (first consequences and then root causes) is suggested, since the failure consequences provide a first prioritisation basis. If the failure consequences are already known, one can start directly with the failure root cause analysis. After completing the second and third main steps of the C&C^2-AFM procedure model, the results are transferred into an extended FMEA documentation template. This template extends the common FMEA by separate columns that add the C&C^2-elements to failure causes and consequences as well as the description of the failure mechanisms. The C&C^2-AFM procedure model is introduced in the following guideline based on the technical system of the gear shift actuation system (Table 1).

Based on various input documents (e.g. QM-, FMEA-reports, etc.) the failure locations are first determined and assigned **(1)** to specific CSS or WSP elements. The question here is: In which element (= affected element) does the failure effect occur (e. g. failure, fatigue, etc.)? In Figure 3 the results of this step are visualized. For the failure mode “linear actor clamps” two failure locations (A and B) where identified, which are in the guide bushes of the actor.

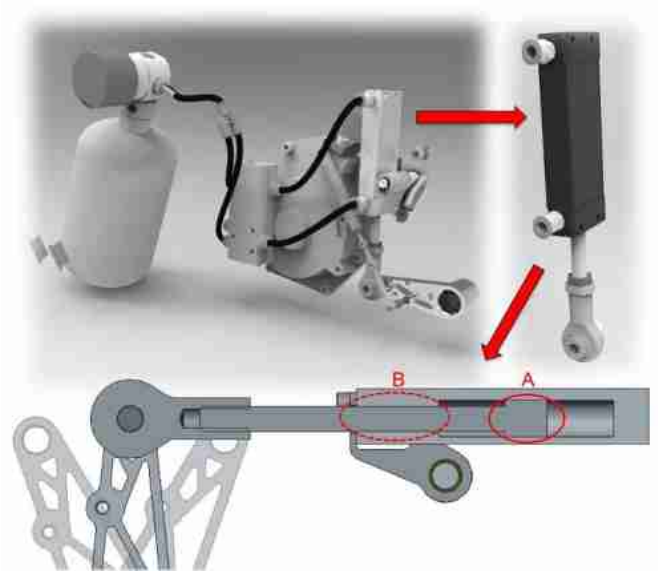

Figure 3: Identifying and specifying the failure location

At this stage it is sufficient if the CSS or WSP elements address whole components or their interfaces instead of their precise geometrical location. However, each of the elements concerned should be assigned a unique identification number and located at least based on a technical cut drawing or CAD model as shown above.

In the next step **(2)**, the identified failure locations are examined individually and based on the embodiment design (technical sectional drawings, CAD, ...), structural models (internal block diagrams, …) as well as state and sequence models, the relevant connectors as well as system states are identified and visualised. The aim is to assign the connectors and their interactions with the system to the corresponding system states. Since the resulting C&C^2-models are limited to the representation of a state, the interface checks as well as the system state prioritization should take place in this step.

Bases on the initially defined failure analysis scope containing the linear actor as well as the gear lever and the mounting bracket, internal block diagrams on different system levels (Lv.1 – Lv.3) were used to identify the relevant connectors, as shown in Figure 4.

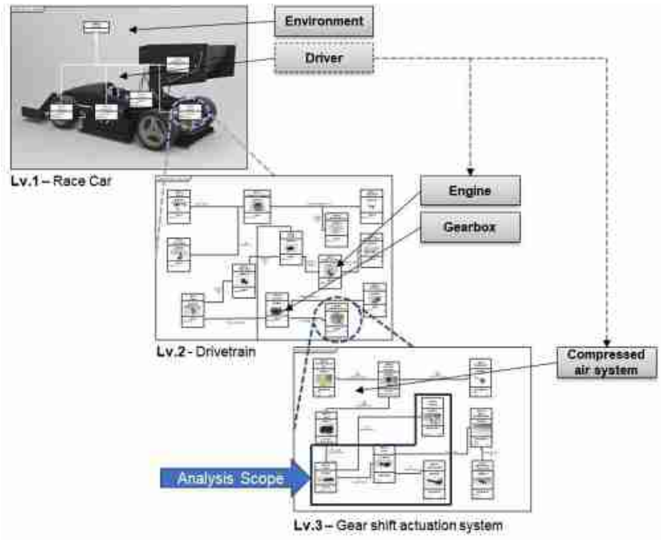

Figure 4: Definition of Analysis Scope and relevant Connectors

Then **(3)** the selected system states are visualised in form of C&C^2-models. The results include multiple Wirk-Nets for failure states. Hereby, the difference between the function and the failure state can be visible in form of variations in the number of elements as well as their arrangement or it can be hidden in their properties. Figure 5 shows the resulting functional Wirk-Net for the selected system state. Three of the four connectors are part of the system function “Shift gears up/down”, whereas the fourth connector (C_{EV}) representing the environmental influences on this function is not connected with the Wirk-Net yet.

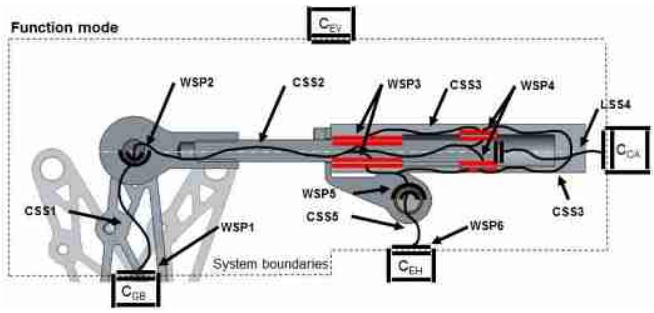

Figure 5: Initial functional Wirk-Net for defined system state with relevant connectors and marked failure locations (red)

At this point there is at least one C&C^2 model that is characterised by an Wirk-Net that connects the failure effect location with relevant connectors. Regardless of whether one wants to determine the failure root causes or consequences, the following procedure steps are very similar.

First **(4)**, **(7)**, the existing (functional) Wirk-Net is examined for inherent failure mechanisms based on undesired chemical or physical effects in the functional Wirk-Nets. These chemical or physical effects are taken from lists as introduced in the state-of-the-art. The properties of the affected element WSP or CSS are first examined and discussed with experts to see whether the resulting failure hypothesis is potentially valid.

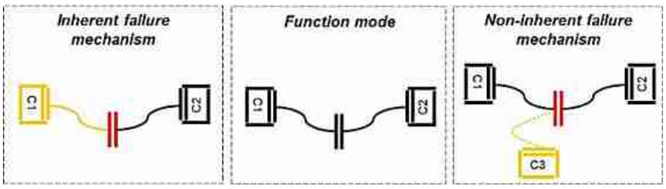

Figure 1: Difference between inherent and non-inherent failure mechanisms

Next **(8)** the external influences are identified based on all relevant connectors. Especially the connectors that are not part of the functional Wirk-Net bear potential to identify the hard-to-find failure mechanisms. In the case of the failure consequence analysis **(5)** the potential impacts on all connectors are checked. This way, non-inherent failure mechanisms are identified in both cases. Accompanying this analysis process, the Wirk-Net is continuously extended by further interactions (between elements) and/or influences (effects of or impacts on connectors) resulting in non-inherent failure mechanisms. Although the relevant elements were defined in the first main step, completion is a creative and collaborative process in which the knowledge of the team (experts) involved plays an essential role.

Finally, a fault tree structure results based on an extended Wirk-Net **(6)**, **(9)**, which is described together with a C&C²-model as shown in Figure 7. Depending on whether the failure consequences **(6)** or root causes **(9)** were investigated, these tree structures resemble an event tree or fault tree. Were both analysis performed, the result is a combination of an event tree and a fault tree – a so called bow-tie diagram. In both cases, the end events are transferred as consequences or root causes, as well as the complete chain of the elements as failure mechanisms to the documentation of the FMEA. During this transfer, care must be taken to ensure that the definition of each element remains consistent and that these models or relevant model sections are linked to the corresponding FMEA scopes. In Figure 7 the event tree is cut at transfer point 5 and the figure focusses more on the visualization of the fault tree and its failure mechanisms. Below the failure mode (ID #13) two failure mechanisms are visualised as two paths – depending on where the heat transfer is coming from. The fault trees can be further extended as shown by the transfer points 1 to 4. In this case it would be suitable to transfer to a process model.

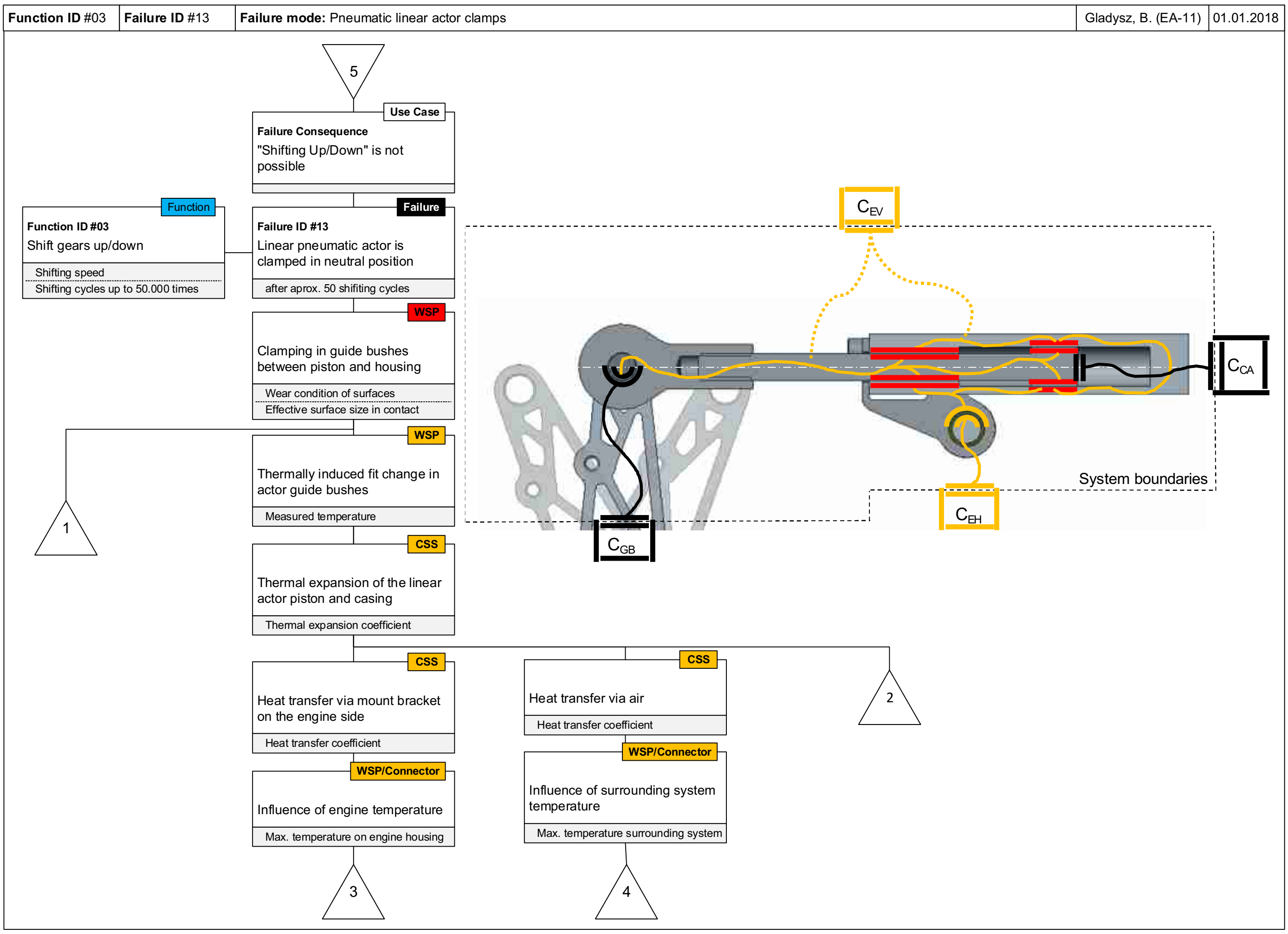

Figure 7: Resulting model based on C&C²-AFM for the function "shift gears up/down" and the failure mode "Linear pneumatic actor is clamped …"

5. Discussion and outlook

C&C²-AFM was developed based on extensive groundwork on the C&C² Approach, eight different application cases based on real technical system and two empirical studies.

C&C²-AFM enables the modeling and analysis of continuous failure mechanisms for a failure mode based on the C&C²-elements Working Surface Pairs (WSP), Channel Support Structures (CSS) and Connectors (C). This approach can be used both to analyse failure consequences and to determine the failure root causes.

By specifying the influences and properties by means of measurable variables ("max. temperature on engine housing"," heat transfer coefficient", ...) the resulting failure mechanisms can be examined not only qualitatively (based on expert assessments) but in a next step also quantitatively (based on calculations, simulation or tests) for plausibility or even for probabilities of occurrence. Furthermore, the more precise failure mechanisms provide guidance in the definition of suitable counter measure to reduce the technical risk.

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