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A FUNCTION- AND EMBODIMENT-BASED FAILURE ANALYSIS METHOD FOR AN IN-DEPTH UNDERSTANDING OF FAILURE MECHANISMS

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Abstract

Research studies have shown that there is an industry demand for improved failure analysis as well as failure documentation and this could be accomplished by model-based failure analysis methods. Furthermore, it is shown that the embodiment of design is an important aspect, which supports the product developer during the design process. Motivated by these findings, the authors combine the Failure Mode and Effect Analysis (FMEA) method and Contact and Channel Approach (C&C²-A). The resulting function- and embodiment-based method focusses on failure mechanisms, thereby improves the analysis and documentation of failures. The results are exemplified and discussed based on two real use cases: the development of a pneumatic gear shift actuation system for a race car and the development of an inline quality control system for a CNC turning machine.

Keywords: Risk management, Product modelling / models, Functional modelling, Knowledge management

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1 INTRODUCTION

The complex nature of product design requires modelling that enables product developers to elaborate, synthesize, evaluate and communicate technical solutions (Andreasen, 1994). Solely for the function modelling domain, there exists a large quantity of modelling methods (Booth et al., 2015; Eckert et al., 2011; Eisenbart et al., 2012; Erden et al., 2008) but only few integrate the element of embodiment of design. As research studies (Breitschuh et al., 2016; Hacker, 1997; Hannah et al., 2012; Juhl and Lindegaard, 2013) have shown the embodiment of design is a key support element during the analysis of technical systems. The necessity to integrate embodiment of design into function modelling (Albers and Matthiesen, 2002) led to the development of the Contact and Channel Approach (C&C²-A). Since then, C&C²-A has been applied in several industrial projects and further developed over the last two decades (Albers et al., 2016; Albers and Matthiesen, 2000; Albers and Wintergerst, 2014).
Regarding a function-based failure analysis, the Failure Mode Effect Analysis (FMEA) or its extension the Failure Mode Effect Criticality Analysis (FMECA) are widely established in industry practice e.g. automotive and aerospace. In past research various key issues with the FME(C)A have been addressed and improved, for example the inadequacies of the Risk Priority Number (Bowles, 2003) as well as the insufficient use of the knowledge potential (Teoh and Case, 2004). Recent empirical studies show that there is a significant demand in industry practice for improved description of failure modes (Zentis et al., 2011) as well as better analysis documentation for future reuse (Roth et al., 2015). Regarding the latter, Roth and Lindemann suggest that "the better documentation could be achieved by model-based methods and especially in connection with formalized analyses." In the following, it is deducted that for such formalized analyses it is necessary to understand the failure mechanisms beyond the failure modes. Motivated by these findings, the authors combine the classical FME(C)A method and the C&C²-Approach resulting in a function- and embodiment-based technical risk analysis. The introduced model-based method focuses on the failure mechanisms, thereby it improves the analysis and documentation of failures. Exemplified by two real use cases: the development of a pneumatic gear shift actuation system for a race car and the development of an inline quality control system for a CNC turning machine. In conclusion, the potentials of the novel approach are critically discussed based on qualitative user feedback from the application.

2 STATE OF THE ART

2.1 Failure Mode Effect Analysis - an overview about current research

The origins of the FMEA method date back to a procedure described by the US Military Standard MIL-P-1629 in 1949, which was revised in 1980 as MIL-STD-1629A (US Department of Defence, 1980). In the automotive industry it was first introduced in the mid-1970s (Matsumoto et al., 1975). The original distinction between FMEA and FMECA, which refers to the criticality assessment including the severity and probability, has become indistinct over the years. The state of the art regarding FMEA improvements can be categorized in research addressing risk identification, risk analysis or risk documentation.
In 1997 Toyota modified the method (Shimizu et al., 2010) in order to address risks caused by product and process change, resulting in the Design Review Based on Failure Mode (DRBFM). DRBFM is a less formalized method, focussing on agile risk identification during the development process. Further research is using creativity methods, such as TRIZ, to support risk identification (Thurnes et al., 2012). However, the FME(C)A as well as the DRBFM cannot sufficiently answer the question about what is causing the failure mode and how the mechanism works (Mathew et al., 2012). "Failure mode is a physically observable change caused by the failure mechanism …", where as the "failure mechanism is the process by which the specific combination of physical, electrical, chemical, and mechanical stresses induce failure" (Hu et al., 1992). This issue becomes crucial, when causing parameters are needed for design change or indicators are needed for system monitoring. This motivation to improve the risk analysis led to the Failure Modes, Mechanism, and Effects Analysis (FMMEA) (Mathew et al., 2012).
Other recent research is addressing risk documentation with the motivation to overcome efficiency issues (Zhang and Li, 2013) as well as knowledge management issues (Renu et al., 2016). As suggested by Roth and Lindemann (Roth et al., 2015) to use model-based methods for risk documentation, there were several SysML-based (David et al., 2010; Schäfer et al., 2015), PLM/CAD-based (Zheng et al.,

2010) as well as ontology-based (Ebrahimipour et al., 2010; Molhanec and Povolotskaya, 2012) approaches introduced and evaluated.
As shown, most of the conducted research is primarily addressing the efficiency and knowledge management issues. Further development of these modelling methods to improve effectiveness of risk analysis with emphasis on failure mechanisms is still a current research gap. The approach to integrate the embodiment of design, e.g. through integration in PLM/CAD, is a step in the right direction due to the embodiment-oriented thinking of product developers during system analysis and synthesis (Matthiesen, 2011). Yet, PLM/CAD-based methods are not sufficient to explain failure mechanisms due to the lack of fundamental elements describing the relations between system function and its embodiment properties. For this reason, a function- and embodiment based modelling approach is proposed to fill the stated research gap.

2.2 Contact and Connector Approach (C&C²-A)

Albers and Matthiesen (Albers and Matthiesen, 2002) extended the model theory of **working surfaces** (Hubka, 1984; Rodenacker and Claussen, 1973; Roth, 1994), as the fundamental element for describing functions and behaviour of systems in the construction methodology, so that the extended model could also be applied to systems involving not only solids but also fluids and fields. "The underlying idea is that a product cannot perform a function without interactions between its components and with its environment **- one component itself cannot perform a function**" (Albers and Wintergerst, 2014). In order to handle the resulting system complexity, it is necessary for product developers to focus on the interfaces and physical structures relevant for the function. These elements form a so-called **effect network**, which stores, transforms and exchanges inputs and outputs, e.g. energy, material and information flows. In C&C²-models, the effect network is composed of the following fundamental modelling elements (Albers and Wintergerst, 2014):

- **Working Surface Pairs (WSP)**, which represent interfaces between these physical structures
- **Channel and Support Structures (CSS)**, which denote permanently or occasionally interacting physical structures of solid bodies, liquids, gases or fields
- **Connectors (C)** modelling elements, which represent the "effect" and the state properties of the environment that is relevant for the function of a system.

A C&C²-model integrates an abstract function into the embodiment of design and specifies the model elements within the effect network. The following Figure 1 shows a C&C²-model, which describes the primary function of a ball-pen "visualise information with a ball-pen". Furthermore, the model provides some examples for model element properties and effects.

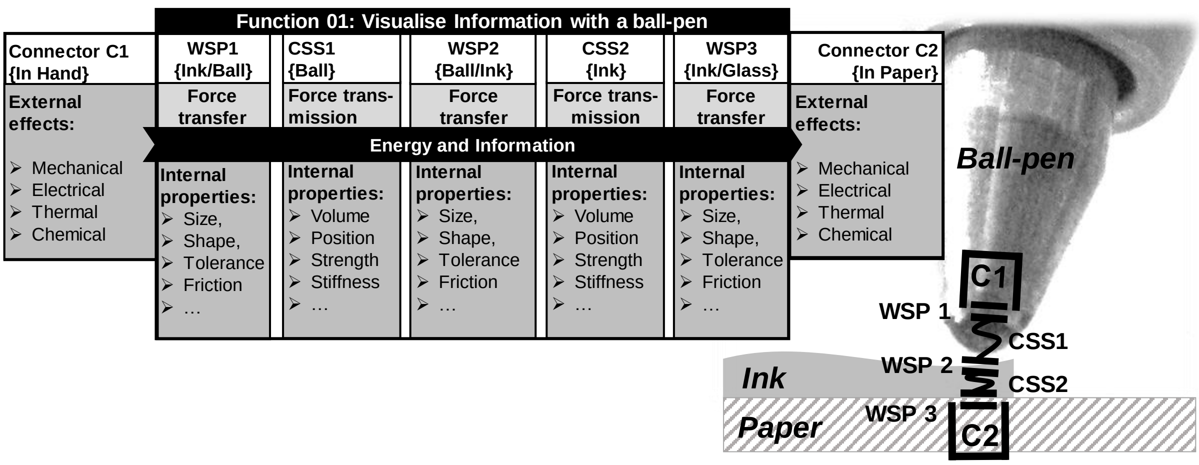


Figure 1: Example for a C&C²-model based on a simple system

The C&C²-Approach has been applied in and has been further developed for different fields of mechanical engineering ranging from lightweight design methods (Posner et al., 2014), topology optimization methods (Albers et al., 2014), change prediction methods (Keller et al., 2007) to visualization of experiment results (Albers et al., 2016) and others. "The Contact and Channel Approach, […] supports analysis by pointing to the lines of state changes throughout an organ structure and thereby throughout the related parts, leading to a fundamental understanding of the functions" (Andreasen et al., 2014). It is not only a "thinking tool" solely for product developers but also an important communication tool for the whole development team (Matthiesen, 2011). To develop it further, it is necessary to implement the approach into software tools with the aim of improving the ability of documentation as well as modelling efficiency. In the past there have been several research projects (Albers et al., 2009; Albers and Zingel, 2013) on the software implementation of the C&C²-Approach. Yet, the resulting tools show potential for improvement in terms of modelling efficiency and complicatedness.

3 CONCEPTION OF THE METHOD

3.1 Preconditions to ensure modelling efficiency

A failure mechanism can be understood as an unintended system behaviour or malfunction. As stated in the previous chapters, a sole function-based approach is not sufficient to analyse failure mechanisms in mechanical or mechatronic systems. The Contact and Channel Approach provides elements that enable the product developer to describe and analyse the function and embodiment relations of a mechanical or mechatronic system. Furthermore, the previously stated stress types (Hu et al., 1992), which induce failures can be specified, visualised and analysed with this approach using the model elements WSPs, CSSs and Connectors.

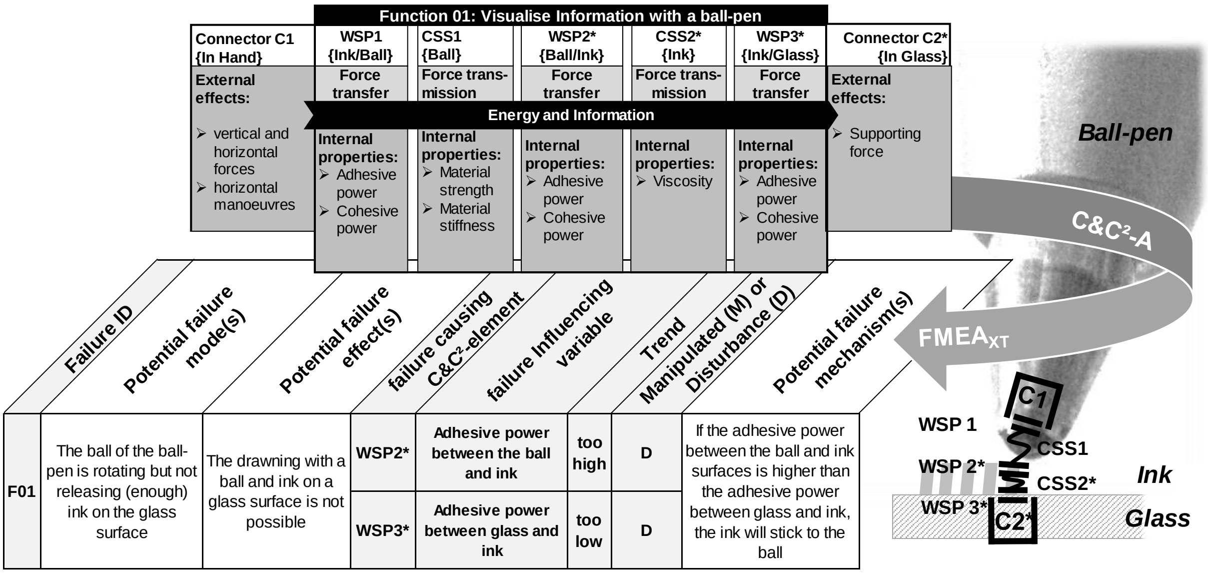
The following method, which is designed for expert workshops, provides an in-depth analysis of failure modes based on their failure mechanisms, hence it is more time-consuming than regular methods. Therefore, a preceding selection of failure modes based on their criticality (severity and probability) is necessary to ensure process efficiency. For this purpose, a regular FMEA approach is used in the beginning. For some failure modes, the failure causes can be sufficiently identified using a Fault-Tree-Analysis (FTA). It has proven useful (Albers et al., 2017) to set a certain criticality level as threshold value, which indicates the necessity to engage the in-depth analysis based on C&C²-A.

Before the actual modelling, the analysis space (subset of the design space) needs to be defined. This space defines the focal area during the analysis and should cover most of the potential failure causes. The relevant external influences from beyond the system boundaries (system environment) are described through the connector (C) model-element. The definition of the analysis space is a trade-off between model accuracy and complexity. Therefore, it is usually an iterative process, because the understanding of the system and its system environment matures during modelling and expert discussions.

3.2 Failure mode and mechanism analysis method based on C&C²-A

The method starts with the comparison of function mode and failure mode. Some failure modes stretch over different system states. Thus, an analysis of their sequence is necessary in some cases to identify the relevant states. This bears analogy to the analysis of a video sequence. There are reference video frames representing the function mode and there are faulty video frames representing the failure mode. By comparing each faulty frame to its reference counterpart, differences can be spotted and analysed leading to the root causes. A similar principle is used in this approach. The mode comparison based on the C&C²-model provides an overview of the changes on the embodiment level. For example, changed energy flows (CSS), added/omitted physical interfaces (WSP) or external influences (C) indicate potential failure effects and causes. Yet, the failure mechanism can only be understood considering the influencing factors, which are either disturbance or manipulated variables. The latter are internal properties describing e.g. the position, material, surface or geometry of the embodiment (Figure 1). Besides position and geometry properties, which apply to both WSPs and CSSs, surface and interaction properties are typical for WSP's, whereas all material properties are typical for CSSs. This way the product developer can narrow down the failure causing properties to certain types represented by each model element. Disturbance variables on the other hand are external (Connectors) or internal (WSPs or CSSs) effects, such as thermal influences or wear.

The failure analysis model described in Figure 2 is based on the example of a ball-pen. Even in such simple cases the cause-and-effect relationships leading to a failure are not trivial. The case explains, why the ball-pen fails on a glass surface and how the failure mechanism works. The causal chain, which leads to the failure effect is stated under "potential failure mechanism(s)". The failure causes as well as the underlying variables are unambiguously assigned to C&C²-model-elements in the C&C²-model. At this stage, the formulated failure mechanisms are merely hypotheses, which were qualitatively derived during expert workshops, and usually require quantitative evaluation (e.g. simulation- or test-based) for verification or falsification purposes. After the evaluation, the probability ratings usually require adjustment and then the scope for alternative solutions can be adapted based on the risk priority. In the case shown in Figure 2, the equilibrium of the adhesive powers in WSP2* and WSP3*, which cannot be adjusted directly (disturbance variable) by the product developer, is causing the failure mode. The function could improve through a change in material combination or surface properties. This example shows that even for such a simple function, four different components need to be analysed and only the full consideration of their interaction during failure mode (failure mechanisms) can help identify suitable solutions.



Failure ID	Potential failure mode(s)	Potential failure effect(s)	failure causing C&C²-element	failure Influencing variable	Trend	Manipulated (M) or Disturbance (D)	Potential failure mechanism(s)
F01	The ball of the ball-pen is rotating but not releasing (enough) ink on the glass surface	The drawning with a ball and ink on a glass surface is not possible	WSP2*	Adhesive power between the ball and ink	too high	D	If the adhesive power between the ball and ink surfaces is higher than the adhesive power between glass and ink, the ink will stick to the ball
			WSP3*	Adhesive power between glass and ink	too low	D	

Figure 2: Failure mode and mechanism analysis explained based on a simple system

This in-depth analysis of failure mechanisms can lead to more detailed failure causes as well as risk priority adjustments. If the resulting models become too complicated, it is possible to split them into two or more separate models instead of compromising the accessibility. The distinction between manipulated or disturbance variables is not only useful during synthesis of solutions but also for direct transfer in to following methods like Design of Experiments (DOE) for test planning purposes.

4 APPLICATION OF THE METHOD

4.1 Application case: Design for robustness and reliability

The following application case is taken from the concept phase of a formula student race car. During that phase, the development team was evaluating different actuation concepts for their gear shifting system. Figure 3 shows the function mode for a pneumatic actuator as part of this gear shifting system.

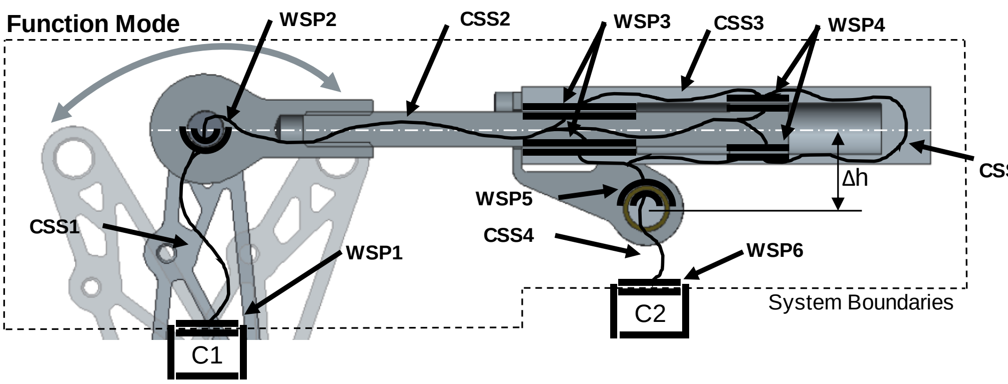


Figure 3: Function mode model of a pneumatic actor as part of a gear shifting system

The C&C²-A based method was applied during expert workshops to analyse failure causes. To enable a rotatory degree of freedom for the pneumatic actuator because of the circular movement of the gear lever (C1), the concept also includes an additional bearing (C2) for the actuator. In the failure mode (Figure 4) the actuator piston is jammed (failure mode), leading to a temporary or even complete malfunction (failure effect) of the gear shifting system. The high severity and probability rating based on expert knowledge led to the C&C²-based in-depth analysis. The failure mode and its corresponding failure mechanisms are visualised in the C&C²-model in Figure 4, whereas the failure mechanism analysis is described in detail in Figure 5.

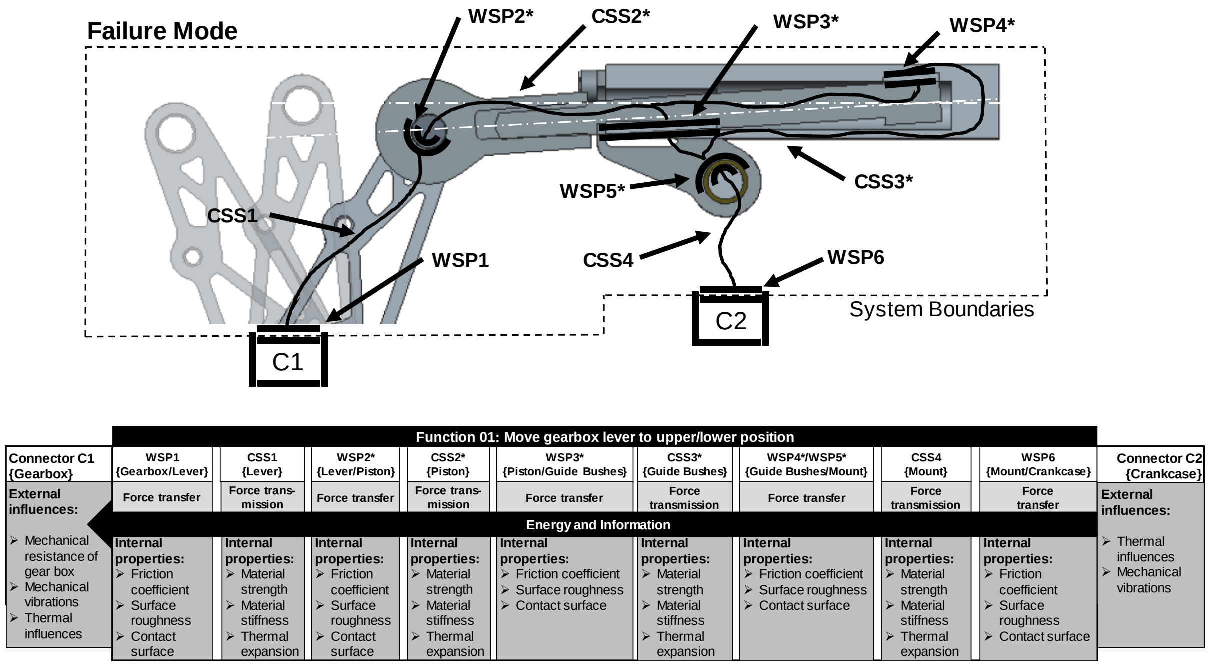


Figure 4: Failure mechanism model of a pneumatic actor as part of a gear shifting system

It starts with the comparison of modes and is leading to a selection of changed model elements. In this failure mode, the elements WSP2, CSS2, WSP3, WSP4, CSS3 and WSP5 have changed from function mode (Figure 3) to failure mode (Figure 5) and are marked with *.

Failure ID	Potential failure mode(s)	Potential failure effect(s)	failure causing C&C²-element	failure Influencing variable	Trend	Manipulated (M) or Disturbance (D)	Potential failure mechanism(s)
F01	The piston of the pneumatic actor is jammed in the guide bushes	Temporary or complete malfunction of the gear shifting system	WSP2*	**Surface roughness because of wear**	too high	D	If the surface roughness is increased because of wear, then the friction coefficient might be significantly increased
F01	The piston of the pneumatic actor is jammed in the guide bushes	Temporary or complete malfunction of the gear shifting system	CSS2*	**Coefficient of thermal expansion**	too high	M	If the thermal expansion coefficient of the actor piston is higher than of the actor housing, then the guide bushes might clamp the piston.
F01	The piston of the pneumatic actor is jammed in the guide bushes	Temporary or complete malfunction of the gear shifting system	WSP3* WSP4*	**Surface roughness because of wear**	too high	D	If the surface roughness is increased because of wear, then the friction coefficient might be significantly increased
F01	The piston of the pneumatic actor is jammed in the guide bushes	Temporary or complete malfunction of the gear shifting system	CSS3*	**Coefficient of thermal expansion**	too low	M	If the thermal expansion coefficient of the actor housing is lower than of the actor piston, then the guide bushes might clamp the piston.
F01	The piston of the pneumatic actor is jammed in the guide bushes	Temporary or complete malfunction of the gear shifting system	WSP5*	**Surface roughness because of wear**	too high	D	If the surface roughness is increased because of wear, then the friction coefficient might be significantly increased

Correlation

Figure 5: Failure mode model including failure mechanism analysis

In the next step the influencing variables (such as external influences or internal properties, see also Figure 1), which can induce the failure mode, are identified and allocated to the C&C²-model elements. In this failure mode, jamming can be caused by hindering the relative movement of the surface due to

increased friction coefficients. In a system with already optimised friction coefficients, the experts concluded that other aspects might influence and change the friction coefficient over time. The two types of changes which were identified during expert workshops are surface roughness because of wear and thermal expansion of materials. These are in the particular failure mode disturbance variables because the product developer cannot adjust them directly.
Based on these analysis results the potential failure mechanisms are determined, specified by influencing variables, which are then allocated to the C&C²-model elements:
For the model elements WSP2*, WSP3*, WSP4* and WSP5* a too high surface roughness due to wear leads to an increased friction coefficient. However, the probability of these causes should be differentiated. According to the experts a higher probability is expected in WSP3* and WSP4* because of higher normal forces. Alternative solutions to solve these failure causes range from changes in material pairings via surface treatments to applied lubrication.
For the model CSS2* and CSS3* a correlation between both influencing factors has been identified, which means the relative thermal expansion of both the piston and the housing should be harmonised. Hereby, the probability should be also differentiated. In case of an internal influence the thermal expansion might be caused by increased friction during extreme gear shifting manoeuvres or in case of an external influence it might be caused by increased waste heat of the engine during high speed manoeuvres. Alternative solutions for these failure causes range from changes in material pairings, tolerances, improved cooling (in case of increased friction) to improved isolation (in case of waste heat of the engine). The friction reduction in WSP3* and WSP4* could help to reduce the overall thermal impact on the system, therefore such correlations should also be considered.

4.2 Application case: Design for quality control

Another application case covers the implementation of the inline quality control system for a CNC turning machine. The case was conducted during a BMBF-funded research project in the field of Industry 4.0 and shall be introduced briefly. The project aims at providing intelligent quality control systems for small and medium-sized companies (SMCs). The quality control systems are developed for three different manufacturing processes, one of these covers a CNC turning machine, which is briefly described in this chapter with a focus on the C&C²-A based method. For a detailed insight, the authors refer to the corresponding publication focussing on the sensor development and implementation (Albers et al., 2017).
The C&C²-A based method was applied to various failure modes identified during the machine process analysis. The preceding evaluation and selection of relevant failure modes led to the failure mode of cutting tool break. In this case, the failure mode was stretching over different system states, which made a state sequence analysis necessary. The following sequential failure mode model shown in Figure 6 illustrates how the cutting tool wear affects the cutting function.

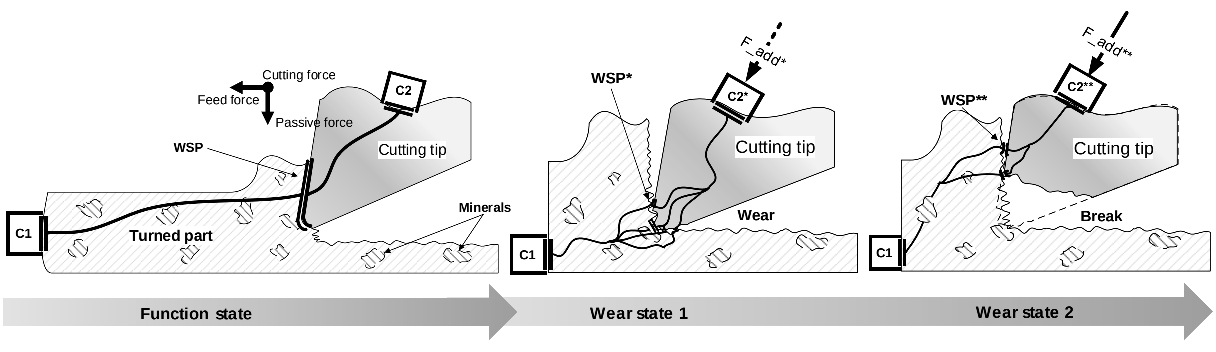


Figure 6: Sequential failure mode model for cutting tool wear in a CNC turning machine

In the middle (wear state 1), the tool tip is already damaged, leading to an ineffective cutting and due to the machine control system, to an increase in applied cutting force. This increase in cutting force (F_add*) is accompanied by a temperature increase in the WSP* due to an increase in local friction. From here on the temperatures and the applied forces are continuously raised until the cutting tip breaks completely (wear state 2). Based on this understanding, the following failure mechanism was deducted in expert workshops based on the models:

The combination of increased cutting force and temperature leads to a break of the tool tip and changes from WSP* to WSP**. The wear of the cutting tool tip is unavoidable (high probability) but the reaction time is improvable by providing measurable indicators for wear state 1 of the cutting tool wear. Applicable alternative sensor solutions range from thermal and force to acoustic sensors, which enable an early identification of wear state 1. Based on this approach, relevant influencing variables have been identified and first DOE-optimised experiments have been conducted (Albers et al., 2017).

5 EVALUATION AND DISCUSSION

As the two real use cases show, the introduced method for failure analysis can be applied to analyse technical systems and it enables an in-depth analysis, which is not provided in a formalized form by current FME(C)A-based methods. Compared to the FMMEA-method, it describes the failure mechanism visually based on C&C²-model-elements supporting the communication with experts during the analysis process. Of course, one can argue that instead of performing this sort of in-depth analysis it is more reliable to go directly in to simulation or testing. The important questions are: "Where to start and where to stop?" If one considers that the preparation of the testing in both application cases for several identified variables took 1-2 months. This shows how much time and costs can be saved through proper qualitative pre-analysis. Hereby, an effective communication between experts during failure analysis is crucial and the integration of function and embodiment in one model view can support it.
In follow-up to the method application cases, the authors gathered the expert feedback on the method. The number of expert participants in each workshops was between five and seven. They noted that the C&C²-A language helps to express ones understanding of the failure mechanism as well as to evaluate the stated failure mechanisms. Although such in-depth analysis is more time consuming than the standard FMEA method, all participants stated that they were more effective during the analysis. They were surprised how their understanding of the technical system improved during the workshops. Several participants stated that the overall efficiency, although there is room for improvement, was sufficient when taking into consideration the quality of the resulting analysis and documentation, which can be used for lessons learnt. Therefore, the initial modelling effort can be considered as a knowledge investment for future product generations and the introduced failure models show an improved knowledge transfer potential compared to current tabular solutions, e.g. FMEA sheets.
On the other hand, several challenges were also identified, which need to be overcome:

- Not all identified failure modes are suitable for an in-depth analysis based on the C&C²-Approach. The failure mode must be of a certain complexity to benefit from the method. Hereby, the length of the causal chain (in form of C&C²-model elements) between effect and cause, the correlations between influencing variables as well as separation of effect and cause by different system states are important indicators for an increased failure mode complexity and should be considered during method selection.
- The risk analysis method as well as the C&C²-Approach need more formalisation in form of an application-oriented guideline. Furthermore, the C&C²-models are currently not self-explanatory for the user. Therefore, a model guidance might be necessary for an efficient knowledge transfer.

6 CONCLUSION

There is a need for an in-depth failure analysis in industry practice, not only considering failure modes, effects and causes, but especially the underlying failure mechanisms based on the embodiment of design. For this purpose, the authors introduced a new analysis method, based on the Contact- and Channel Approach (C&C²-A) and presented the benefits of an integrated function- and embodiment-based failure analysis model on two real use cases. The introduced method should not be understood as an alternative to FME(C)A but rather as an extension. Therefore, the method as well as the tools were designed and chosen for compatibility with FME(C)A. So far the overall qualitative feedback from the participants showed that the method improves the effectiveness of failure analysis leading to a better system understanding and helping identify the root causes. On the other hand, the authors also identified several challenges, especially regarding efficiency. Further research will address the mentioned points in chapter 5 and especially focus on a further formalisation and better tool implementation of the method. Regarding method evaluation, the next steps will include several experiments, which shall provide a quantitative evaluation of this method and a comparison to other established methods e.g. FMEA regarding efficiency and effectiveness.

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