NordDesign 2018
August 14 – 17, 2018
Linköping, Sweden

How do C&C²-models improve the understanding of system behaviour in failure analysis?

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Abstract

In previous publications a new approach has been introduced based on the Contact and Channel Approach (C&C²-A), which integrates embodiment design with cause and effect relations in one model. Previous results showed apart from an increased efficiency and comprehensibility a more peripheral and holistic analysis scope compared to isolated models for the embodiment design (CAD) and the cause and effect relations (fault trees). The latter has enabled the user not only to identify further failure causes, but also to determine more complex failure mechanisms that lead to hard-to-find failure causes.
However, in the previous publications the underlying enablers for an improved understanding of system behaviour in failure analysis using a C&C²-based approach could not be analysed in detail. For this reason, a further study is presented in this paper. The resulting observational study was conducted with 22 participants comparing the integrated C&C²-models in a real-world failure analysis with isolated models for embodiment design (CAD) and cause and effect relations (FTA, SysML-ibd).

Keywords: Model-based failure analysis, Observational study, Contact and Channel Approach (C&C²-A), Internal block diagrams (ibd), Fault tree Analysis (FTA)

1 Introduction

The model-based failure analysis for the systematic determination and analysis of failure causes and consequences continues to be attested a high relevance in the product development practice

of mechatronic as well as mechanical systems. Often the models, which are used to support the failure analysis, lack essential information to fully understand the system behaviour and thus establish hypothesis for the underlying failure mechanisms. In previous publications (Gladysz & Albers, 2018a; Gladysz, Spandl, & Albers, 2017) a new approach for failure analysis has been introduced based on the Contact and Channel Approach (C&C²-A) (Albers & Matthiesen, 2002), which integrates embodiment design with cause and effect relations in one model. The approach was evaluated (Gladysz & Albers, 2018b) in comparison to isolated models for embodiment design (CAD) and cause-effect relationsship (fault tree models) and the results showed apart from an increased efficiency and comprehensibility an extended analysis scope and understanding of system behaviour. The latter has enabled the product engineers not only to identify further failure causes, but also to determine more complex failure mechanisms that lead to hard-to-find failure root causes. In this way it was shown that the approach has a positive influence on the effectiveness of the failure analysis.
However, in the previous publications the underlying enablers for an improved understanding of system behaviour in failure analysis using a C&C²-based approach could not be analysed in detail. For this reason, an observational study was conducted with 22 participants comparing the integrated C&C²-models in a real-world failure analysis with isolated models for embodiment design (CAD) and cause and effect relations (Fault Tree, Internal Block Diagram). An early prototype of Schaeffler's eBoard served as application case during the study.

2 State of the art

2.1 Necessity for model-based approaches in failure analysis

FMEA (Failure Mode and Effects Analysis) is well established as failure prevention method across various industries. Studies have shown that there is a need for a more precise description of technical risks (Zentis, Czech, Prefi, & Schmitt, 2011), which also include the description of failure modes of technical systems. Furthermore, less experience-driven, more formalised failure analysis approaches are necessary (Roth, Gehrlicher, & Lindemann, 2015). Roth and Lindemann (2015) conclude that a model-based approach is needed to support the FMEA in order to address this issues. This need is not new as shown in a very recent and extensive state-of-the-art review of the FMEA method (Spreafico, Russo, & Rizzi, 2017). Yet, still there is a "lack of proper models (e.g. Multi-physics) to describe cause and effects chain" (Spreafico et al., 2017). In order to address this research gap, Gladysz et al. (2017) introduced a model-based approach that is based on the Contact and Channel Approach (C&C²-A), which was originally introduced by Albers and Matthiesen (2002) and further developed over the years.

2.2 A C&C²-based approach for failure analysis

The C&C²-Approach (C&C²-A) supports the analysis of system effects and influences of the embodiment design using product models of design practice (sketches, drawings, CAD-Models etc.) (Albers & Wintergerst, 2014). These system effect and influence relations enable system functions and behaviour. For this purpose, the C&C²-A provides three basic elements and a set of rules for modeling that are required for C&C²-models. These following basic elements (Matthiesen, 2002; Matthiesen, Grauberger, Sturm, & Steck, 2018) form the so-called Wirk-Net (Albers & Wintergerst, 2014), which describes the energy, material and information flows within a technical system and between corresponding systems:

"**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."

"**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."
"**Connectors (C)** 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."

A Wirk-Net can be also applied to describe the causal chain of physical and chemical effects that lead to a failure occurrence and finally to multiple possible failure consequences (Gladysz & Albers, 2018a). These physical and chemical causal chains or processes are called failure mechanisms (Hendricks, Williard, Mathew, & Pecht, 2015; Mathew, Alam, & Pecht, 2012). A Wirk-Net-based description of failure mechanisms is illustrated in Figure 1 below using the example of a pneumatic linear actuator. In this case a jammed system state is modelled, which is caused by an unequal thermal expansion of housing and piston, which in turn are caused by thermal environmental influences.

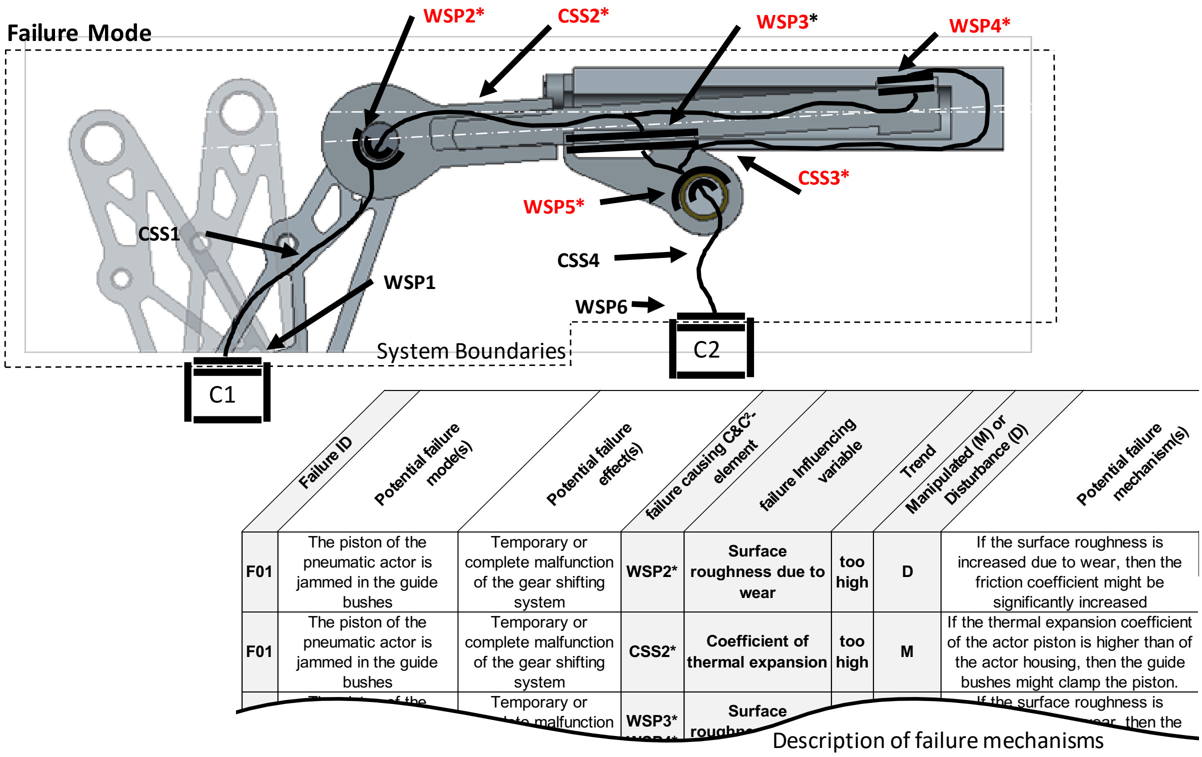

Figure 1: Modelling failure mechanisms with the C&C²-Approach according to Gladysz et al. (2017)

2.3 Previous application results and further research needs

Previous studies with a total of 80 participants have shown that "the use of C&C² models in failure analysis has a positive effect on the efficiency, the comprehensibility as well as the scope of the analysis" (Gladysz & Albers, 2018b). These studies were able to prove a measurable added value through the application of C&C²-models (C&C²-M) in failure analysis compared to a combined approach using FTA, FMEA and CAD. Yet, the conducted studies did not provide enough insight on the application of the C&C²-approach as well as the role of the embodiment design information during failure analysis. The latter one is especially interesting because there are other model-based approaches (such as internal block diagrams in SysML), which describe a Wirk-Net-similar structure yet without the embodiment design information. Therefore, this research contribution focusses on a detailed analysis of the failure analysis processes to answer the question: how do C&C²-models improve the understanding of system behaviour in failure analysis?

3 Research methodology

Due to the broad research question, an observational study with individual participants was conducted. It allows to eliminate the disturbing influences of a group effect and to get a very detailed insight into the individual approach of each participant. A total of 22 investigations were carried out based on four failure cases and three different approaches: the C&C²-based approach, a SysML-ibd-based (internal block diagram) approach and a FTA-based (fault tree analysis) approach. Afterwards, the subjects were interviewed about their approach and impressions. 19 of the participants were master students and three of them were engineering experts at Schaeffler. The educational background of the participants was mainly in the mechanical domain (68%).

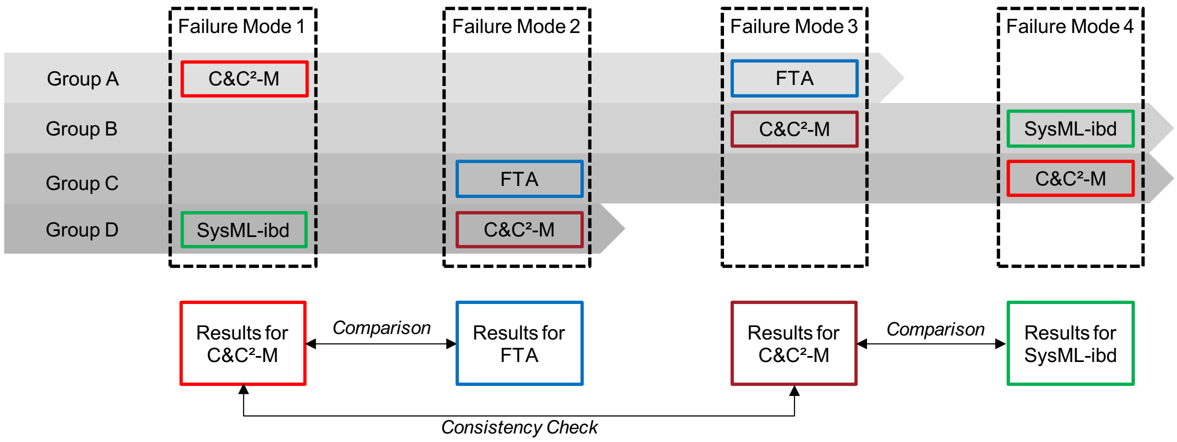

Figure 2: Test design showing the allocation of the test groups to failure case and analysis approach

For this study a test design with repeated measurement was selected as shown in Figure 2, due to limited number of available participants and especially experts. Due to the time constraints, each participant applied two different approaches. Furthermore, this way, it was ensured that each analysis approach is investigated on at least two failure cases. For this reason, the experimental design presented includes four test groups and four failure cases. The results of Group A and C, Group B and Group D are compared to ensure that each method was performed on at least two different failure cases and in a different order. The study was conducted in cooperation with Schaeffler providing a technical application case in form of an early prototype of Schaeffler's eBoard as well as four possible, exemplary failure modes (see Figure 3), which were identified and refined together with experts from Schaeffler for the particular application.

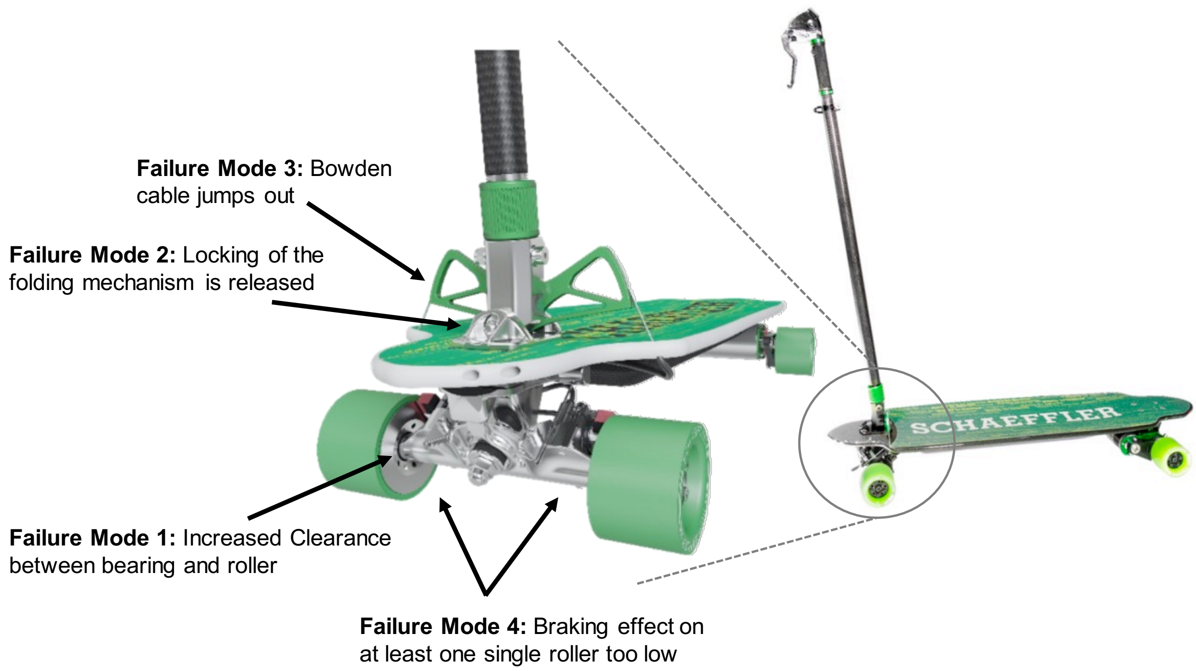

Figure 3: Application case for the study – Schaeffler's eBoard and four possible, exemplary failure modes

The time schedule of the observational study includes a compact introduction to the technical system (3 minutes) as well as the procedure based on the FMEA (5 minutes) by the moderator. Subsequently, the analysis approach and the failure mode including the subsystems were introduced (10-13 minutes). The analysis approaches were introduced based on videos and pre-defined examples, this way a possible distortion effect was reduced. This procedure was repeated for the second failure mode and analysis approach. The participants had a total of 15 minutes for failure analysis. In the end, the participant defined technical measures and gave feedback in the form of a semi-structure questionnaire and an open discussion.

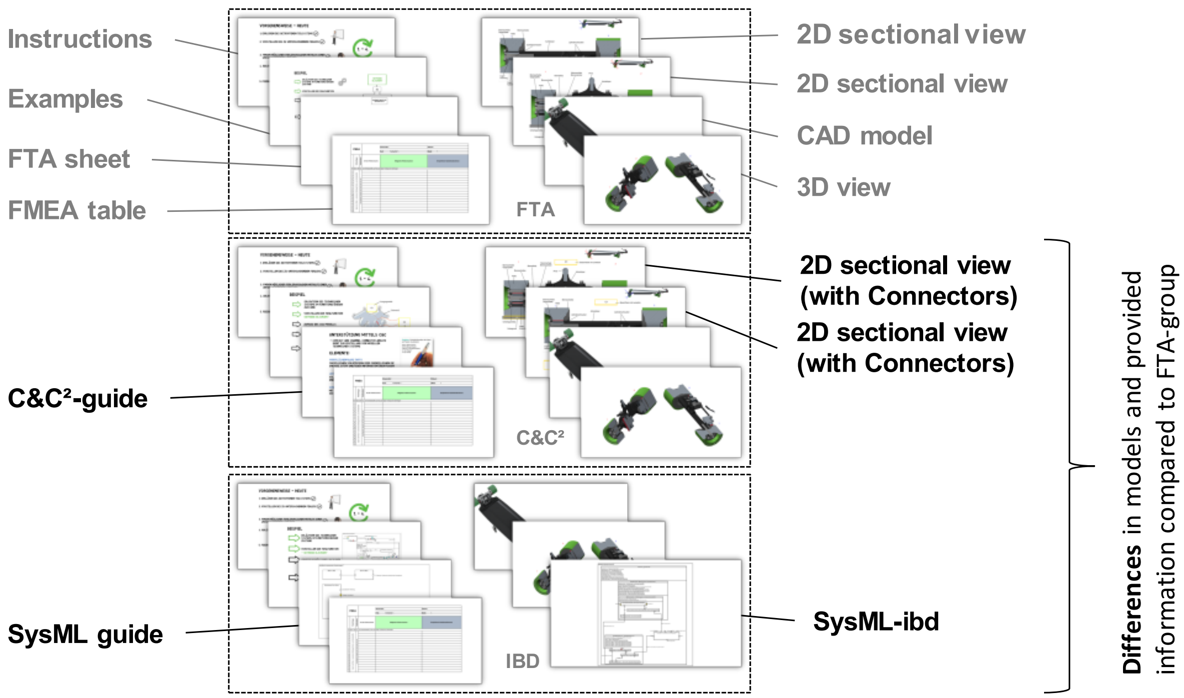

Figure 4: Overview about the provided documents highlighting the differences between the approaches

As shown in Figure 4, each participant was provided with an introduction to the procedure, an example case for each approach, a method template and the FMEA table, a CAD model and a 3D view. The FTA and C&C² users had the same 2D views with the difference that for the C&C²-based approach the failure effect locations (WFP or LSS) and the connectors were already drawn in, to compensate for the increased modelling effort with C&C²-A. The SysML users on the other hand had a SysML-ibd (internal block diagram) instead of the 2D sectional views, to compensate for the information advantage of the extensive ibd-model. Additionally, the digital CAD models were available to all participants. All documents, except for the digital CAD models, were only provided in printed form.

4 Empirical findings

First, it was examined whether the proportion of identified failure causes that can be assigned to the system behaviour varies between the different approaches. In addition to the system behaviour, the following domains were differentiated for this purpose.:

- Engineering Processes **(EP)**
- User Behaviour **(UB)**
- Environmental Influences **(EI)**
- Use Cases **(UC)**
- System Behaviour **(SB)**

The previous studies (Gladysz & Albers, 2018b) primarily focused on how the analysis scope is extended within the domain of the system behaviour and environmental influences. In this study the analysis scope is widened - in the sense of a continuous failure analysis -, and further domains are included in the investigation. If, for example, a failure cause occurred during a "temporal superimposition of braking and steering", then the failure cause would be assigned to the category “Use Cases”. These assignments were made retrospectively using the principle of dual control and based on the failure descriptions and the observation log.

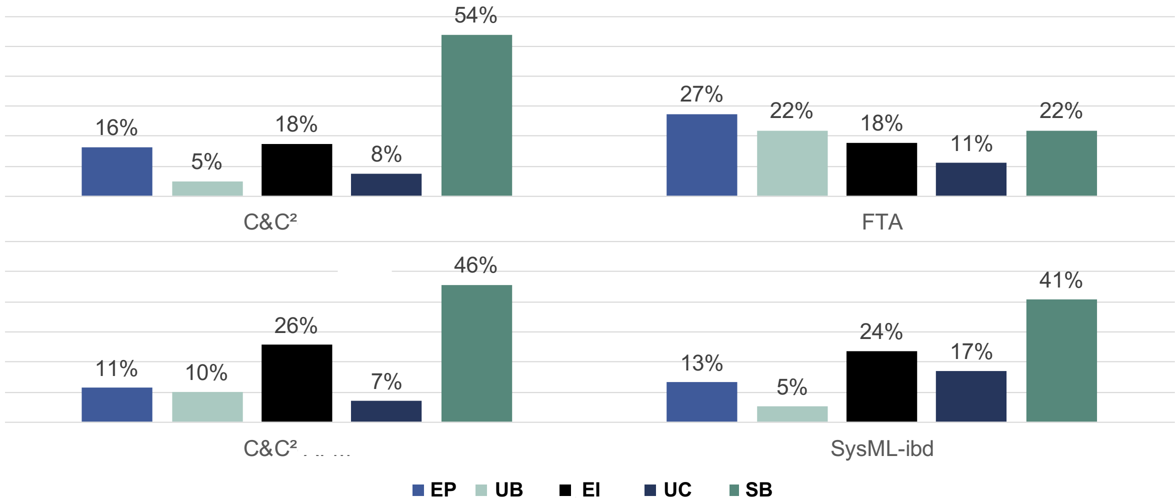

Figure 5: Domain distribution for each analysis approach

Figure 5 shows the evaluation of the domain distribution for each analysis approach. The two comparison groups are shown one above the other. First, it can be stated that the resulting distribution profiles for C&C²-models show a very similar pattern in both cases, which proves the reproducibility of the gathered data. Hereby, the failure analysis and the resulting failure mechanisms are mainly focused on the system behaviour as well as environmental influences. Most of the remaining failure causes are assigned to the Engineering Processes domain. In comparison to the FTA it is noticeable that the identified failure causes show a tendency towards the Engineering Processes domain and the proportion of failure causes assigned to system behaviour decreases by 32% compared to C&C²-models. The distribution profiles of C&C² models and SysML-ibd are very similar. In detail, the resulting failure causes for the C&C²-based approach are little more focussed on system behaviour, environmental influences as well as user behaviour.

In the next step, it was examined from where the participants obtained the information for determining the failure causes. On the one hand, the participants were asked to "think out loud" during the failure analysis, so that the procedure could be logged. On the other hand, the documents used were recorded at intervals of 30 seconds, so that a history of the information sources resulted for each identified failure cause. Identifying the failure causes requires an interplay of expert knowledge as well as detailed system and contextual information. Within the scope of this study, it was determined which of these factors was decisive for the identification of the failure cause. The impact of expert knowledge is differentiated in direct transfer and deduction, whereas context information is differentiated in embodiment design and effect and influence relations information. This results in the following four input categories, which allow a multiple assignment of failure causes, depending on the documented procedure that led to identification.

- Deduction based on expertise
- Direct Transfer based on experience
- Usage of embodiment design information
- Usage of effect and influence relation information

If, for example, the user already knew the failure cause from previous engineering experience, then this was categorized under " Direct Transfer based on experience". If this is deductively derived based on domain-specific expertise, the failure cause is categorized under "Deduction based on expertise". If the user primarily viewed the CAD model, the 3D views or the 2D sectional views during the period before the analysis, this is categorized under "Usage of embodiment design information". Whereas the consideration of the SysML-ibd models represents a pure consideration of effect and influence relations. C&C² models represent an integrated view and are allocated accordingly to both categories.

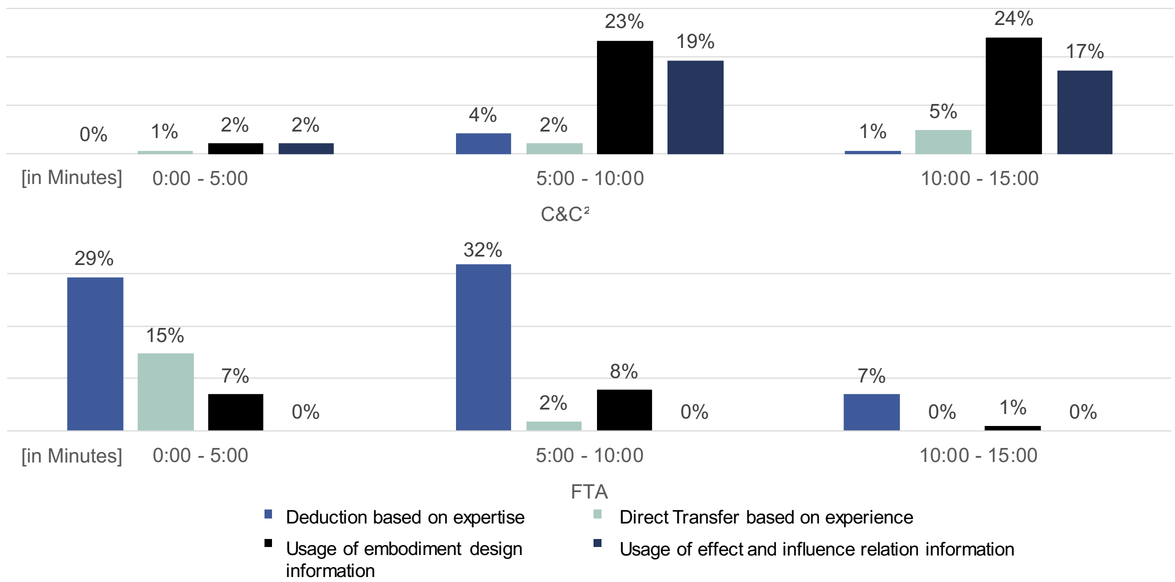

Figure 6: Allocation to input categories during failure analysis for C&C² and FTA

The resulting allocation to the input categories, which were decisive in identifying the failure causes, are regarded over time during failure analysis. Figure 6 as well as Figure 7 show the allocation to the four input categories for both comparison groups separately. For this purpose, the failure analysis is divided into three phases of 5 minutes each. Figure 6 shows the comparison group C&C² and FTA. Hereby, it can be determined that in the case of FTA, especially in the first two phases, the most failure root causes are identified and more than in comparison to C&C². This is since C&C²-modelling takes place in the first five minutes and is more time-consuming than FTA modelling. The factor distribution also clearly shows that the amount of deduction and direct transfer are dominant as expected in the FTA. FTA-users have studied the 2D sectional views intensively, so that some of the identified failure causes can also be traced back to embodiment design information. In the case of the C&C²-based approach it can be determined that the impact of embodiment design information is slightly higher than of interdependencies information. This deviation describes the situations in which users have additionally used the pure embodiment design models in form of the digital CAD-model.

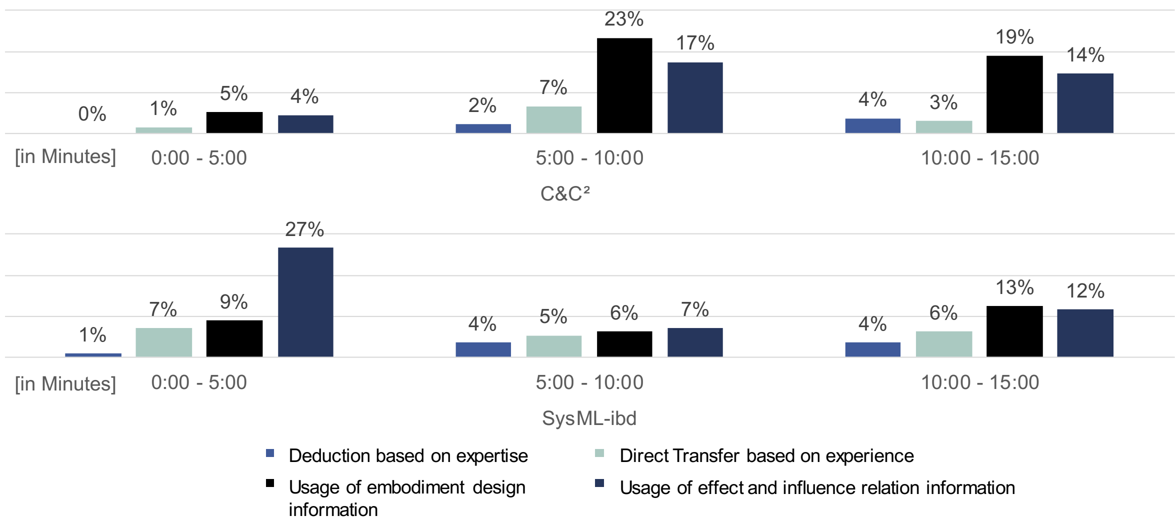

Figure 7: Allocation to input categories during failure analysis for C&C² and IBD

Figure 7 shows the evaluation of the factor distribution for the comparison group C&C² and SysML-ibd. The profile of the factor distribution over the phases for C&C² is very similar in comparison between Figure 6 and Figure 7 and the slight differences are due to the different failure modes. Similar to the FTA, the factor distribution for SysML-ibd shows an intensive identification of failure causes in the first phase, because unlike FTA and especially C&C², no additional modelling is required here in the beginning. However, this effect already subsides in the second phase and in the third phase more embodiment design information is applied to support the failure analysis. From the second phase onwards, the SysML-ibd approach shows a more balanced distribution between the four factors compared to the other approaches.

5 Discussion

The results of the observational study have shown that the different approaches and the underlying models enable different degrees of freedom as well as "stimulate" different impulses during failure analysis:

- **IBD**-based approaches are particularly suitable for providing an efficient overview of the already known interdependencies at system structure level. However, ibd-based approaches often require additional domain specific information for in-depth analysis and should be therefore used only coupled with supplementary models such as CAD.

- **FTA**-based approaches enable users to detach themselves from the limitations of individual domain-specific models when identifying and describing the failure mechanisms. This allows more freedom in integrating interdependencies through experience-based knowledge transfer or based on model-based information. On the other hand, it can lead to shortened, incomplete or not plausible causal chains.
- **C&C²**-models provide the highest information density. At the same time, the results also reveal disadvantages of an isolated application of C&C²-models. Within a single domain – e.g. mechanical domain, the approach leads to a very comprehensive analysis of failure mechanisms, which, however, are often not continuously analysed across domain boundaries.

Based on these findings, the authors conclude that a C&C²-based approach for failure analysis requires a superordinate structure that enables continuous failure analysis across domains. The profile of the FTA - as shown in Figure 6 - contrasts with the C&C²-based approach and shows synergy potential. SysML-ibd and FTA have a degressive performance curve, allowing a quick identification of failure causes in the front-end and middle phase of the failure analysis. C&C²-A requires a purpose-oriented development of the models at the beginning, so that the failure analysis shows a progressive performance curve corresponding to the model maturity increase over time.

This way, different sequences of failure analysis approaches are possible in order to further optimise the overall failure analysis performance. The approach to start with also depends on the knowledge level of the user. The learning-by-modelling character of a C&C²-model or a SysML-ibd is more suitable for novice users, while system experts could start directly with FTA and then perform very specific in-depth analysis using the C&C²-based approach. However, the failure analysis should end with FTA to enable a continuous investigation of failure mechanisms across domains e.g. Engineering Processes.

6 Summary and outlook

The results of the observational study have shown that the embodiment design of the system and corresponding models that depict it are an essential information source for the identification of failure causes. As a result, participants who used SysML models or used FTA structures more often resorted to the provided technical drawings or CAD-models compared to the participants who used the C&C²-based approach. Furthermore, the study showed that the participants need a model of the technical system, which they can use for orientation during failure analysis. SysML-based as well as C&C²-based approaches provide such a model on different granularity levels. Whereas the scope based on the SysML-ibd is wider, the SysML-ibd provides less information for defining failure cause hypothesis or identifying complex failure mechanisms.

Based on this and other findings from the study, the authors derive recommendations for the model usage in failure analysis, the sequence as well as the suitability. The resulting findings and recommendation are used for further development of the C&C²-based approach, the so-called C&C²-AFM (Analysis for Failure Mechanisms) (Gladysz & Albers, 2018a) approach.

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