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HOW DO C&C²-MODELS IMPROVE EFFICIENCY, COMPREHENSIBILITY AND SCOPE IN FAILURE ANALYSIS - AN EMPIRICAL STUDY BASED ON TWO LIVE-LABS

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Abstract
In this article, the authors evaluate a newly-developed method, which is based on the Contact and Channel Approach (C&C²-A) and uses models integrating embodiment design and functions for supporting the collaborative failure analysis in product development. Previous interview-based investigations of the method have already showed a potential regarding comprehensibility, extension of the analysis scope and improvement of efficiency. To quantify the effects, a two-study comparison with conventional models and approaches was conducted and the results are introduced and discussed.

Keywords: risk management, empirical studies, functional modelling

1. Introduction
The demand for effectiveness and efficiency of failure analysis methods is omnipresent in research as well as in manufacturing companies. However, the increasing failure density and complexity across disciplines cannot be handled solely with automated approaches. Far too much knowledge is implicit and build on years of experience with previous product generations or other related technical systems. To satisfy this demand for improved effectiveness and efficiency it is important to further improve collaborative failure analysis methods. For this reason, the authors introduced a newly-developed method (Gladysz et al., 2017), which is based on the Contact and Channel Approach (C&C²-A) and uses models integrating embodiment design and functions for supporting the collaborative failure analysis. In this paper, the authors aim to provide a two-study comparison with conventional models and approaches regarding effectiveness and efficiency in collaborative failure analysis processes. Two laboratory studies with selected and project-experienced Master's students (total of 80 participants) were conducted and evaluated. The failure cases were taken from real product development projects in the field of automotive drivetrain engineering - a pneumatic gear shift system as well as a high-pressure pump for gasoline fuel injection. In the first study, analysis efficiency and comprehensibility of the results are evaluated based on a comparison between integrated and separated models for embodiment design and functions. In the second study, the analysis scope is evaluated based on a comparison between the newly-developed method and fault trees.

2. State of the art

2.1. Relevant approaches and studies in the field of failure analysis
FMEA (Failure Mode and Effect Analysis) is a well-established failure prevention method in numerous industries. Yet, the method as well as the failure analysis approach bear potential for improvement. The

industry is critical about the experience-based application and the often inadequate description of technical risks (Zentis et al., 2011). In recent state of the art, model-based approaches are being proposed as a possible solution to the problem (Roth et al., 2015). However, there are already numerous model-based approaches, ranging from SysML-supported (David et al., 2010; Schäfer et al., 2015) to CAD/PLM-based (Zheng et al., 2010) and ontology-based (Ebrahimipour et al., 2010; Molhanec and Povolotskaya, 2012) approaches. What is the difference to the approach developed by the authors? Many of these approaches rely on formalization and automation to achieve higher efficiency and effectiveness. In the future, the increasing complexity will mean that decision-makers will be faced with the choice of whether to use automation for a broader analysis or to investigate with teams of experts in detail (Schnellbach, 2016). Not all failure cases can be examined based on formalized and automated approaches, so a systematic selection of failure cases will become more important (Gladysz et al., 2018). Regarding the suitability of in-detail failure analysis approaches, a review over the last 40 years of FMEA research shows that there is still a "lack of proper models (e. g. Multi-physics) to describe cause and effects chain" (Spreafico et al., 2017). The newly-developed approach by Gladysz et al. (2017) addresses this gap.

2.2. Analysis of failure mechanisms based on the C&C²-Approach

The approach is based on the Contact and Channel Approach according to Albers and Matthiesen (2002). The core of the approach is the visual description of cause-and-effect relationships at the level of embodiment design using three C&C²-elements. On this basis, a so-called Wirk-Net (Albers and Wintergerst, 2014) is formed that can describe the interdependencies of the behaviour of a system and thus describe both functions and failures. It describes the energy, material and information flows using the three C&C²-elements: Working Surface Pairs, Channel Support Structures and Connectors (Albers and Wintergerst, 2014; Matthiesen et al., 2018):

- "**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** 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."

Based on this understanding, the authors have developed an approach which, by systematically analysing the Wirk-Net based on the failure location, enables systematic elaboration of failure mechanisms (Mathew et al., 2012; Hendricks et al., 2015) and thus the identification of the failure root causes or consequences. The approach is illustrated in Figure 1 using the example of a pneumatic actuator. In this case, the actuator is jammed due to the uneven thermal expansion of the housing caused by the engine waste heat. The C&C²-elements WSP2, CSS2, WSP5 and CSS3 in Figure 1 represent a potential failure cause location, while the Wirk-Net between them and the failure effect locations WSP3 and WSP4 span the failure mechanism.

Previous interview-based investigations of the method have already revealed a potential regarding comprehensibility, extension of the analysis scope and improvement of efficiency in the collaborative failure analysis. However, due to a lack of empirical research on the C&C² approach, it was not possible to quantify the effect nor to prove the correlation with the models used. This research gap is now addressed in this article.

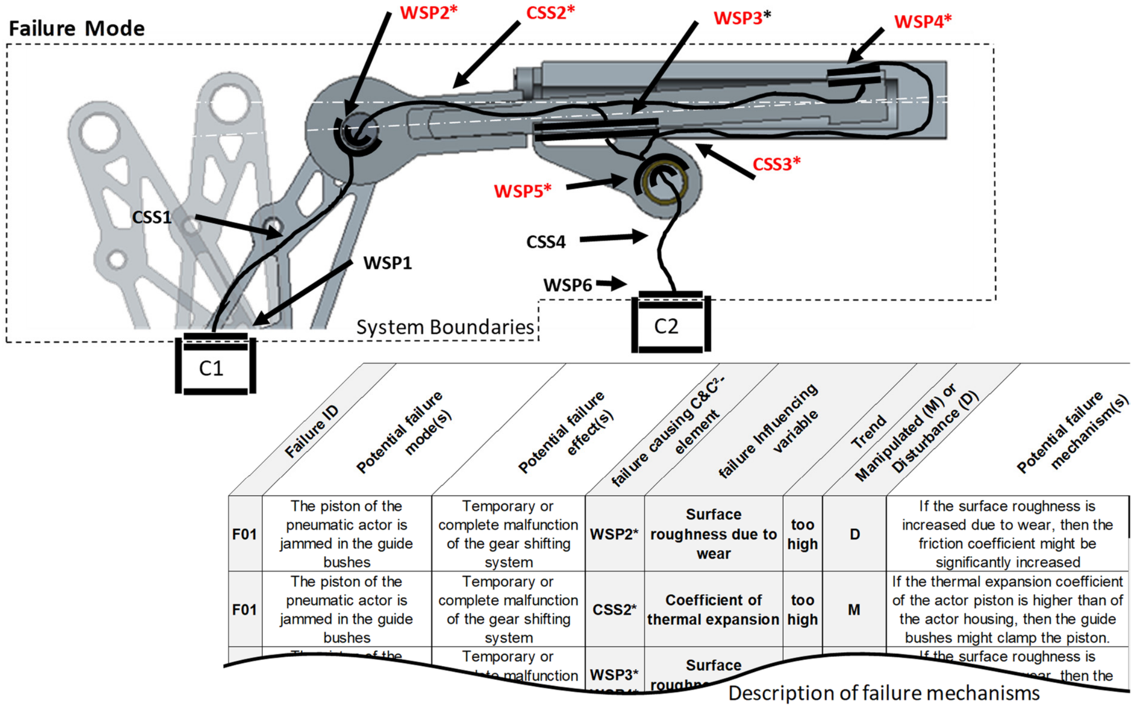

Figure 1. Modelling failure mechanisms with the C&C²-Approach according to Gladysz et al. (2017)

3. Research methodology

Starting from the research hypothesis that the collaborative application of the C&C²-based method leads to an improved efficiency, analysis scope and comprehensibility of the failure analysis, key criteria were first defined, and operational hypotheses were formulated. Subsequently, a suitable survey design was developed. The following operational hypotheses have been established for this purpose:

- ***Hypothesis 1*** **- Number of identified failure causes per time** is higher using an integrated embodiment design and function model (C&C²-A) compared to separated models (CAD drawings, Internal block diagram)
- ***Hypothesis 2*** **- Comprehensibility of failure analysis** is higher using an integrated embodiment design and function model (C&C²-A) compared to separated models (CAD drawings, Internal block diagram)
- ***Hypothesis 3*** **- Failure analysis scope** is extended using the C&C²-based Wirk-Net compared to logical structuring approaches (fault trees)

Ensuring comparability and measurability has made a high degree of standardisation necessary. For this reason, the authors have decided to conduct a laboratory study in a controlled environment. Due to the time and effort involved and the large number of participants required, it was not possible to conduct a study in this format with industry experts. As a substitute, both studies were conducted with Master's students (in Mechanical Engineering) who have already gained development experience in Live-Labs. These Live-Labs have a duration of several months and enable the Master's students to participate and learn in a co-creation product development process together with industrial partners (Albers et al., 2017). The very homogeneous participant base is a key factor, which simplifies comparability across the groups. The transferability of these findings to heterogeneous teams was not the focus, so that a potential disadvantage was accepted in the survey design.

While the first study focused on hypothesis 1 and 2, the second study focused on hypothesis 3. All 80 study participants had already basic up to advanced FMEA expertise as well as overall product development experience at the time of the experiments. The participants were divided into two groups (test and control group) and in teams of three or two. Figure 2 summarizes the structure and characteristics of the two studies. Both studies have a similar survey design and comprise three different failure analysis tasks. Furthermore, the test group differed from the control group in both studies primarily by the given method and as well as by the supporting input models.

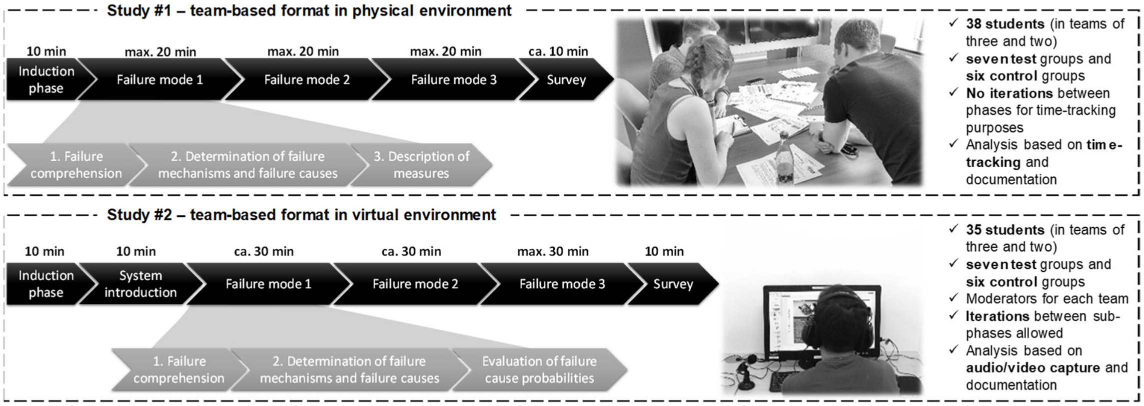

Figure 2. Overview of the two laboratory studies, their structure and characteristics

Study #1 was conducted with a total of 38 students from the Live-Lab "Integrated Product Development 2016/17" in a physical and team workshop format. Due to the fact, that the teams did not need to generate the models, a standardized introduction to the survey as well as to the documents was sufficient. In order to examine the efficiency, the participants were asked to identify as many failure causes as possible and to describe them as precisely as possible. For evaluation purposes, the times between each phase as well as sub-phases were tracked. Furthermore, all participants were asked to fill out a questionnaire. Afterwards, all the documented results were examined and rated by two independent experts familiar with the technical system.

Study #2 was conducted with a total of 42 students (including seven moderators) from the Live-Lab "ProVIL 2017" in a virtual and moderated team workshop format. To investigate the effects on the analysis scope, which serves as a key factor for analysis effectiveness, the degree of freedom in modelling was increased for this study. The decision to switch to a virtual environment was motivated by the fact that disturbing influences can be reduced, and the argumentations can be recorded completely. To mitigate differences in methodological knowledge, both groups were supported by moderators. The moderators took over a control function to ensure that the methods and models are applied correctly. For this purpose, the moderators were trained in the methods in detail beforehand in a separate workshop. For evaluation purposes, the screen and audio casts of each team were recorded.

While the first hypothesis can be directly evaluated based on the measured times as well as the amount of identified failure causes, the second and third hypothesis required the definition of indicators. For this survey, comprehensibility (hypothesis 2) was defined based on the indicators: *assignability of the cause to embodiment design*, *precision in the description of the cause* and *plausibility of the cause*. Figure 3 describes the evaluation scheme with key questions and defined characteristics of the criteria. The evaluation was performed by two independent experts familiar with the technical system. In addition to the pure comprehensibility value a corrected value was defined, which also takes the number of identified failure causes as well as the phase duration into account.

To examine the effect that the applied method has on the failure analysis scope (hypothesis 3), it was necessary to measure the distance between the failure location and the failure cause. Therefore, each identified failure cause (226 in total for study #2) was situated based on the technical system. A shell model was used for this purpose, dividing the technical system into three zones. The *primary analysis area* (Zone1) is located where the failure directly occurs. Around this area is the *extended analysis area* (Zone2) located. The second area is still within the defined system boundaries. It includes subsystems which interact with the failure location. Failure causes, which were located and identified on the drawn system boundaries or beyond, were assigned to the *peripheral analysis area* (Zone3). All identified failure causes of both groups were classified according to this principle.

INDICATORS	EVALUATION SCHEME		KEY FIGURE
Assignability of identified cause On the basis of the description of the cause, do you know which components of the technical system are affected?	0	Cause cannot be assigned to the subsystem or is incorrectly assigned	**Comprehensibility of a single identified cause**
	1	Cause can be assigned vaguely to several components	$Q_{FUi} = \left(\frac{\{0;1;2;3\}}{3} + \frac{\{0;1;2;3\}}{3}\right) x \frac{\{0;1\}}{1}$
	2	Cause can be assigned to a component or an interface without specific location	
	3	Cause location can be unambiguously located at the component or interface	
Precision of cause description The cause has been assigned at least one relevant and above all measurable property (or parameters) (geometry property, material property, etc.)?	0	Description of causes does not address properties or influencing factors	**Average comprehensibility of a team's failure analysis**
	1	Cause description refers to system properties/influences	
	2	Causal system properties or influencing factors can be measured	$QTn = \frac{\sum_{i=1}^{j} Q_{FUi}}{j}$
	3	A tendency is assigned to causing properties or influencing variables	j = number of identified causes per team per failure mode
Plausibility of identified cause Is the identified cause plausible in relation to the technical system and taking the failure context into account?	0	Causality between cause and failure mode is not comprehensible	
	1	Causality between cause and failure mode is comprehensible	

Figure 3. Criteria for comprehensibility evaluation of the resulting failure analysis

4. Empirical results

The failure cases for both studies were taken from real product development projects in the field of automotive drivetrain engineering - a pneumatic gear shift system (Gladysz et al., 2017) (shown on the left side of Figure 4) as well as a high-pressure pump for fuel injection (Gladysz et al., 2018) (shown on the right side of Figure 4).

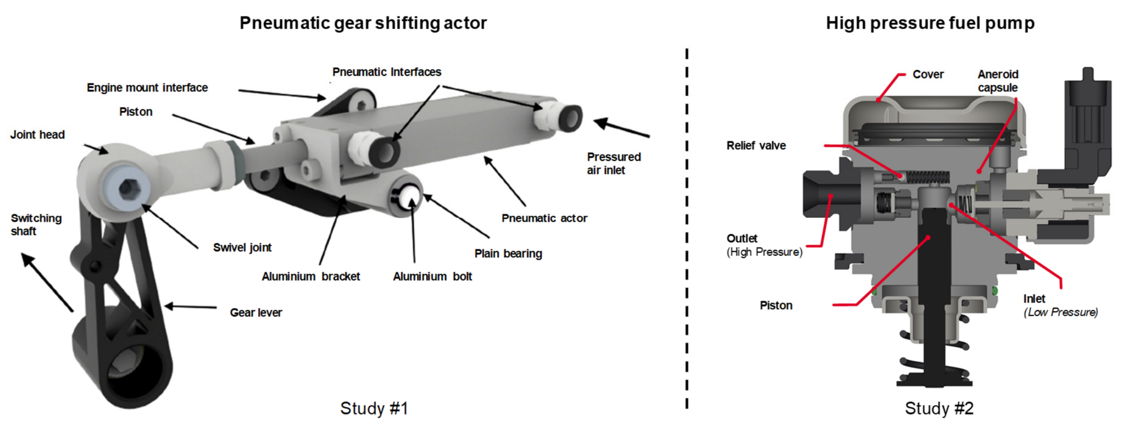

Figure 4. Technical systems used in the studies

The statistic evaluation of the hypothesis was based on nonparametric tests, since most of the dependent variables had no normal distribution. Due to the study design with two groups - a test as well as a control group - statistical tests for two-sample cases were needed. In order to compare differences between two groups, the Mann-Whitney U test was used for independent groups, while the Wilcoxon Signed Ranks test was used for dependent groups according to Reuschenbach (2009). Due to the relatively small sample size, it was not the asymptotic but the exact (2-sided) values for both tests that were calculated. Hereby, the relevant values are the p- and the r-value. The p-value smaller than 0.05 describes a significant difference between both groups. Whereas the r-value describes the effect strength, which is categorized according to Gignac and Szodorai (2016) in to small effect (r=0.1), typical effect (r=0.2) and relatively large effect (r=0.3)

In the following, the results of the first and then the second study will be presented. Beginning with an introduction of the failure modes and the survey process.

4.1. Results of the first study

To investigate the first and second operational hypotheses, three differently complex failure cases were used, which originated from the development of a pneumatic transmission shift actuator for a race car (on left side of Figure 4):

- ***Failure Mode 1:*** Plain bearing breaks
- ***Failure Mode 2:*** Aluminium bracket bends
- ***Failure Mode 3:*** Piston clamped

The differences between the groups regarding the content provided were only in the explanation sheet of the failure and the documentation form. The explanation sheet included a C&C²-based model of the function and malfunction. Furthermore, the probands received a documentation form in which the failure root causes could be assigned to the individual C&C²-model elements (similar to Figure 1). In the control groups, instead of the C&C²-models, simplified sketches of the functional and failure state were provided in the explanation sheet, showing the same system behaviour. The documentation of the failures causes in the control groups was based on a standardized FMEA template, which was reduced to the essential extent. The counter measures for the identified causes were documented in the same way for both groups. In addition, both groups were able to access the system structure in internal block diagrams as well as printed CAD drawings specific for each failure case. Since only selected functions and associated failures were considered, the survey design did not include a comprehensive functional structure.

Test Statistics	Failure Mode 1 n/min	Failure Mode 2 n/min	Failure Mode 3 n/min
Mann-Whitney U	136,500	172,500	81,000
Z	-1,245	-0,177	-2,879
p	0,220	0,862	0,004
r	0,202	0,029	0,467

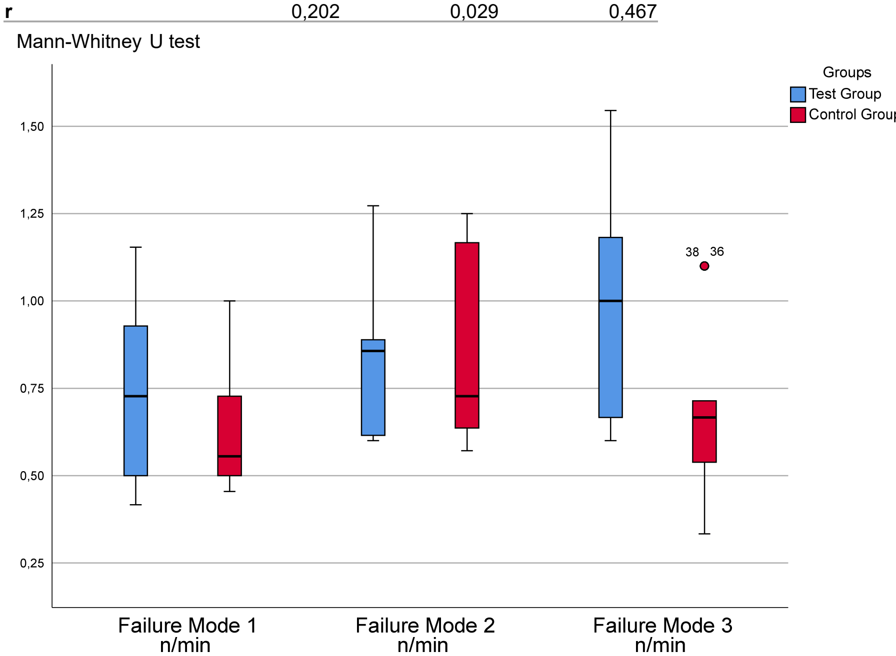

Figure 5. Study #1: Evaluation of the analysis efficiency between both groups

Prior to the start of the test, both groups were advised to describe the root causes of the failure as precisely and measurably as possible by means of system properties (e.g. surface roughness) and underlying external influences (e.g. thermal influences or external loads). All groups had a familiarization period of 10 minutes. For each of the three failure modes, the teams went through three phases as shown in Figure 2. In the first phase, the participants should first become familiar with the failure mode and then start with the failure analysis.

The analysis efficiency was evaluated based on the quotient of the recorded phase duration for the failure analysis per failure case (Figure 5). Hereby, the Mann Whitney U test reveals a significant difference between test and control group as well as a large effect strength in the third failure mode, while the second one shows the slightest difference in the boxplot diagram. Interestingly, the third failure case was judged by the participants of both groups to be the most complex and the second as the simplest. The control group was considerably faster on average in the second failure case, but also identified fewer failure causes in this case. The data shows that the more complex the failure case is, the higher is the efficiency gain based on C&C²-models. Conversely, this means that in the case of a simpler failure mode, less or even no efficiency advantage can be expected from an integrated consideration of the embodiment design and function context based on a C&C²-model.

The comprehensibility rating was conducted based on the documented results by two independent system experts in accordance with the indicators and formulas in Figure 3. Hereby, a total of 326 causes were systematically rated. The control group results were rated based on the FMEA form, while for the test groups the corresponding C&C²-models were additionally considered. Figure 6 shows the absolute ratings (left side of the boxplot diagram) between those two groups based on the comprehensibility key figure. It can be stated that the pure comprehensibility values are significantly better for the models of the test groups for all three failure cases. To check whether efficiency gains were achieved through poorer description quality of the documentation, the values were corrected by the amount of failure causes and the phase duration values. The results for the corrected comprehensibility values are also shown in Figure 6 (right side of the boxplot diagram). They show an approximation of both groups in the second failure case, due to the faster output of the control group in this failure case. In the first and third failure case the Mann Whitney U test still shows a significant difference between both groups based on the corrected values for comprehensibility. Furthermore, the measured effect strength is large across all failure cases.

Test Statistics	Failure 1 Quality	Failure 2 Quality	Failure 3 Quality	Failure 1 Q*n/min	Failure 2 Q*n/min	Failure 3 Q*n/min
Mann-Whitney U	2,000	3,000	0,000	5,000	8,000	3,000
Z	-2,714	-2,571	-3,000	-2,286	-1,857	-2,571
p	0,005	0,008	0,001	0,022	0,073	0,008
r	0,440	0,417	0,487	0,371	0,301	0,417

Mann-Whitney U test

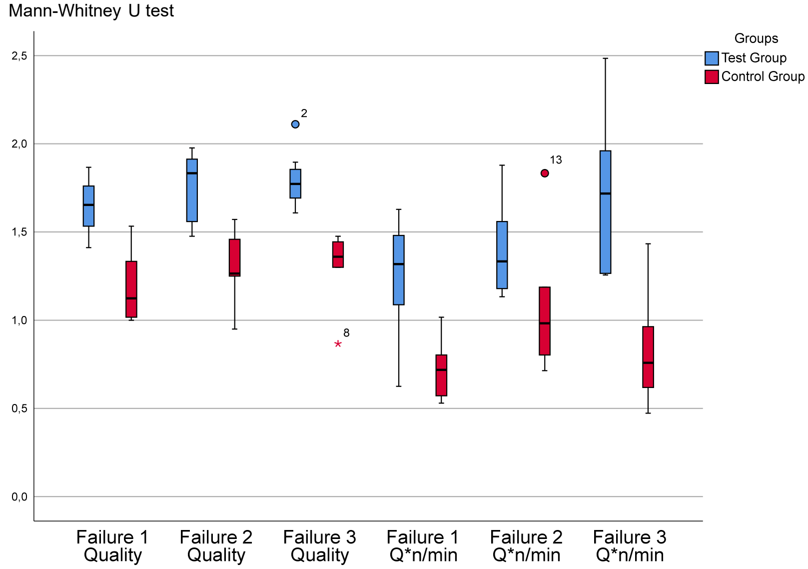

Figure 6. Study #1: Evaluation of the analysis traceability between both groups

The investigation of the questionnaire allowed the authors to get an understanding of the self-perception of the participants during failure analysis. The questionnaire results (Figure 7) regarding the relevance of secondary models in the second failure case revealed that the test group extended the analysis scope compared to the control group. This means, they did not focus solely on the failure effect location. The control group probands classify the technical drawing with a narrow component view (see bottom of Figure 7) as more relevant than the system view showing the system interactions. The opposite behaviour can be seen in the test group, here the probands rank the component view down and classify the system view as more relevant.

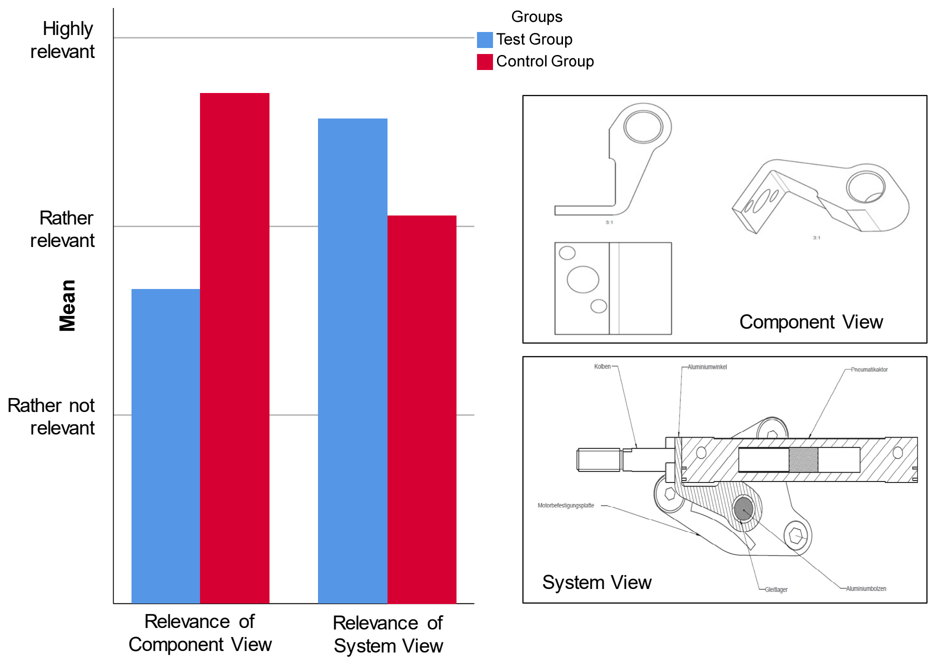

Figure 7. Study #1: Evaluation of the analysis focus between both groups for the second failure case

In summary, the results of the first study show that both a significant efficiency gain in failure analysis and a significant improvement in comprehensibility are possible through an integrated modelling of embodiment design and function in failure analysis. At the same time, it is concluded that the degree in efficiency gain is correlated with the failure complexity. This correlation will be further discussed in Chapter 5.

4.2. Results of the second study

To investigate the third operational hypothesis, three different failure cases of varying complexity were used, originating from the development of a high-pressure pump (on right side of Figure 4).

- ***Failure Mode 1:*** Piston clamped
- ***Failure Mode 2:*** Leakage on the piston seal
- ***Failure Mode 3:*** Pressure valve opens below defined value

The provided content differed between both groups in the form of modelling templates, the list of physical and chemical stresses as well as the guidelines for the analysis approach. Instead of using C&C²-based templates, the control groups worked with fault tree templates. The list of physical and chemical stresses contained different types of wear, corrosion, fretting, creep, fatigue and deformation based on the state of the art (Tumer et al., 2003; O'Halloran et al., 2012). Hereby, the lists for the test groups were sorted by C&C² elements, whereas the lists of the control groups were structured directly by physical or chemical effects.

Prior to the start of the study, all groups received a one-hour introduction to the organisational procedure of the experiment, the software used and the methodical procedure. The latter was the only difference between the two groups in the introduction. The participants were then distributed to soundproof and uniformly air-conditioned individual cabins equipped with a screen, keyboard, mouse, microphone and headphones. The collaboration of the individual teams took place in a conference-like and document-based environment, whereby cloud applications were used. In contrast to the first laboratory study, the training period served primarily to familiarize the probands with this new virtual working environment, supported by the moderators. Subsequently, the probands had another 10 minutes to familiarize themselves with the technical system of the high-pressure pump. The technical system was new for both the probands as well as the moderators at the time of the experiment, so that previous knowledge could be excluded. Like in the first laboratory study, the probands went through the three failure modes sequentially, but had 30 minutes per failure. In contrast to the first laboratory study, the duration of the individual sub-phases "Failure Comprehension", "Determination of Failure Mechanisms and Causes" and "Evaluation of failure cause probabilities" were also limited in time and were accordingly controlled by the moderators. This was defined to achieve a maximum analysis scope in each group and for each team under the given time limit. This also means that, based on the second study, no statements can be made about efficiency differences between the groups.

Test Statistics	F1_Zone1	F1_Zone2	F1_Zone3	F2_Zone1	F2_Zone2	F2_Zone3	F3_Zone1	F3_Zone2	F3_Zone3
Mann-Whitney U	12,000	17,500	4,000	10,500	7,000	20,500	8,000	9,000	5,000
Z	-1,304	-0,676	-2,473	-1,552	-2,085	-0,073	-1,913	-1,825	-2,383
p	0,234	0,628	0,014	0,138	0,051	0,945	0,073	0,101	0,022
r	0,201	0,104	0,382	0,239	0,322	0,011	0,295	0,282	0,368

Mann-Whitney U test

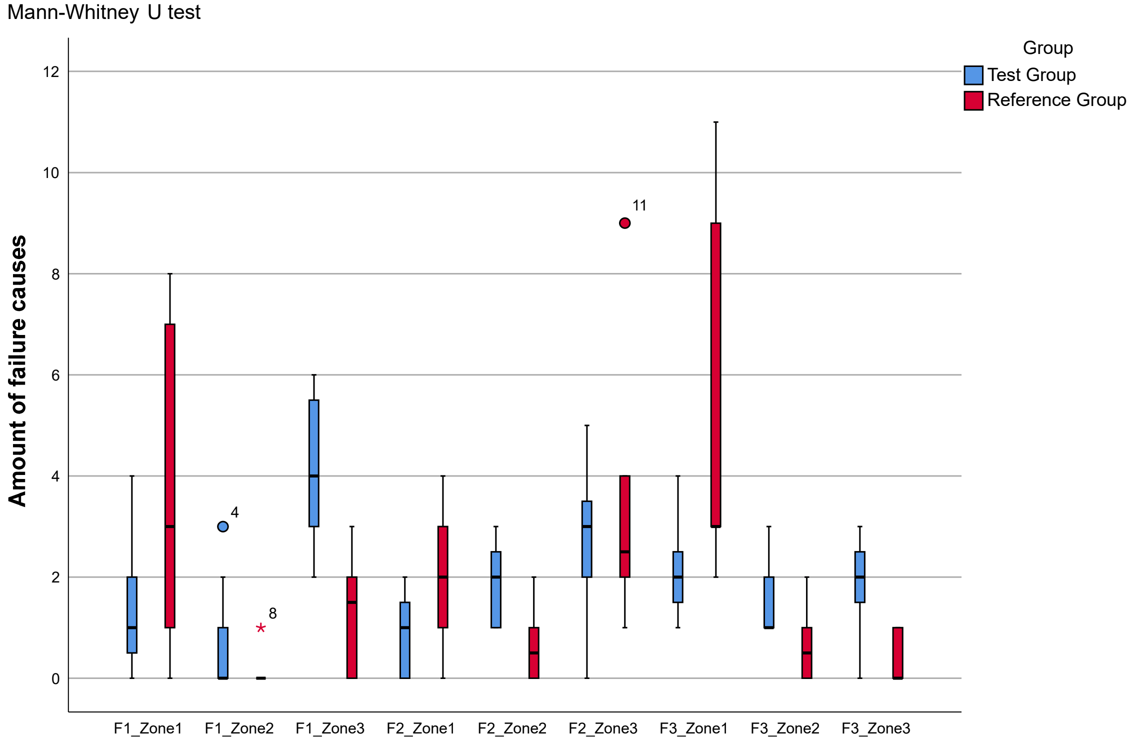

Figure 8. Study #2: Evaluation of the systemic focuses between both groups

Figure 8 compares the distribution of the failures causes between both groups based on the provided CAD drawings, which were precisely the same. In addition, the groups' CAD drawings featured a $C\&C^2$-model overlay. As described in Chapter 3, all failure causes were then allocated to a three-zone model for each failure case separately. The first zone represents a narrow analysis scope on the failure effect

location, while the third zone represents external influences on the system. All groups were asked to state the location of the identified root causes as precisely as possible in the provided documentation sheet, therefore this information was used for allocation of the root causes within the three-zone model. Hereby, it can be observed that the control groups have focused strongly on the primary zone. In contrast, the test groups have located the failure root causes further away in the peripheral areas. The significant differences (based on the Mann Whitney U test), especially for failure mode 1 "*Zone3*" and failure mode 3 "*Zone3*", illustrate the different approaches of both groups.
In summary, it can be concluded that the control groups oriented more towards the lists of physical and chemical stresses rather than the provided models for identifying the causes of failures. Furthermore, a significant difference in the distribution of the failure root causes between the control and test groups was found. The latter findings state that the test groups are using the Wirk-Net of the C&C²-models to build their failure mechanisms (in terms of causal chains) systematically from failure effect location to external influences, which are defined by the Connector-elements.

5. Discussion of the study results

How meaningful is the efficiency gain from the first study? Considering that the initial modelling effort was not considered, the absolute values cannot be used as a reference or orientation measure. However, it is not unlikely that for both groups, there is a similar initial modelling effort. For the control group, at least the preparation of the technical drawings and the schematic failure mode sketches would have to be considered. Nevertheless, the authors estimate that the initial modelling effort of the C&C² models will be higher in most cases, due to the higher information volume and density. In addition, the gain in efficiency depends to a large extent on failure complexity. The failure complexity can be understood in analogy to a fault tree as follows: The more branches and levels the tree has, the more complex the failure is. In this context, a branch can be understood as a failure mechanism that is examined from the point of failure to its root. The more complex the failure, the more sophisticated the failure analysis approach needs to be. However, the failure complexity can only be assessed retrospectively, therefore the authors introduced an approach for identification and prioritisation of potentially complex failures (Gladysz et al., 2018) based on the change of technical requirements as well as the technical system.
Regarding the comprehensibility of the documented failure causes, an improvement on the basis of model-based failure documentation could be demonstrated, which can be attributed in particular to the allocation of failure causes to properties and influences of C&C²-elements. The assignment of failure causes to WSP, LSS and Connector elements increases the comprehensibility for the receiver of the failure analysis, especially in combination with the corresponding C&C²-models. This enables the user to better follow the argumentation chain of the analysis report. This is particularly important in the collaborative assessment of technical risks, as the combination of mechanisms and their triggers (root cause) determines the probability of a failure occurring and the whole risk assessment teams must have the same understanding.
The evaluation of the second study has shown that the scope during the failure analysis is significantly extended with C&C²-models. This has been proven with Failure Mode 1 and Failure Mode 3. Extended does not only mean that the failure mechanisms become longer in terms of geometrical distance, but that also areas of the system are uncovered and analysed in detail, which are important for a function fulfilment and which do not stand out in the CAD model. This was particularly evident in Failure Mode 2, where two preload springs of the seal were only considered as a possible failure cause in the test groups. The comparison of the resulting fault trees with the C&C² models shows another interesting conclusion: The failure mechanisms between control and test groups do not differ significantly in the number of elements. The main difference lies in the fact that the users, based on the C&C² models, orient themselves based on the Wirk-Net when forming the failure mechanisms. However, the Wirk-Net is limited to the physical and chemical domain. A fault tree is not tied to a domain, so that the group can switch between the system and the process domain within their failure mechanism.

6. Summary and outlook

In this article, the authors evaluated a newly-developed method, which is based on the Contact and Channel Approach (C&C²-A) and uses models integrating embodiment design and functions for supporting the collaborative failure analysis in product development. For this reason, a two-study comparison with conventional models and approaches regarding effectiveness and efficiency was conducted and the results introduced and critically discussed.

Based on the presented empirical results, it could be demonstrated 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. Hereby, the latter measure was used as an indicator for analysis effectiveness. As explained in Chapter 5, this does not mean that the use of C&C²-models is always useful and adds value in every failure analysis case. This applies particularly, as this contribution only examined the suitability of the approach and the models focussed on the mechanical domain. Furthermore, this article should be understood much more an evaluation of method and model potential and less a precise recommendation for action in failure analysis assessments.

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