Investigating qualitative modelling in design - experimental method validation at the Contact and Channel Approach

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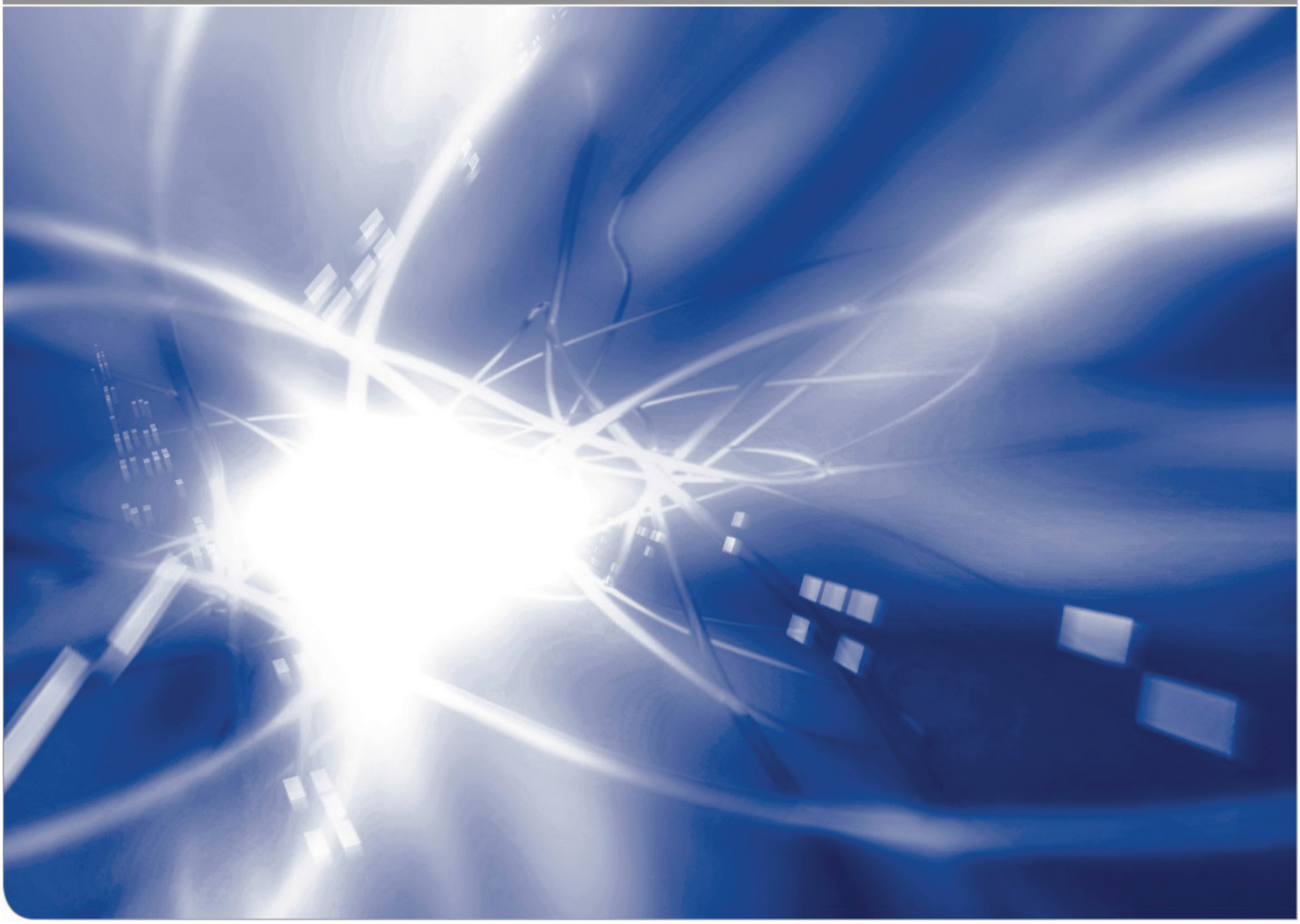

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Qualitative modelling in embodiment design aims to support the gain of system understanding. However, it remains unclear whether using a qualitative modelling method impacts system understanding compared to intuitive approaches.

In this contribution, an experimental study is conducted to investigate the impact of the modelling method based on the Contact and Channel Approach on system understanding. The study is set up with 35 participants, video-based modelling training and two technical systems. The tasks are analyses of causes for system behaviour on two different detail levels of system understanding. The control group solves the task with intuitive approaches, the test group uses the modelling method. On the system level, general relations of embodiment and behaviour are investigated. On the detail level, function-critical system areas, as well as function-relevant system states, are investigated.

The modelling method increases understanding of technical systems at the system level compared to intuitive approaches. In the detail level, no statement about statistically significant differences could be derived. Challenges in identifying critical areas and relevant system states are uncovered, which provide insights for improving the modelling method. With this study design, the modelling process is now observable. It can provide a baseline for investigations of similar modelling methods.

Keywords: embodiment design; design research; method validation; experimental study

1 Introduction

In embodiment design, the details of the embodiment of a technical system must be defined in a way that enables it to fulfil its intended functions. The initial activities necessary for identifying the details of the embodiment relevant for its behaviour and resulting functions are often done intuitively. Design engineers think about the system and make assumptions about the relations of embodiment and behaviour. This mental analysis can be supported by qualitative models. These models can be applied in a lean and quick way, as they don't need a quantitative definition of the product (e.g. CAD model).

To make use of the advantages of qualitative models, design engineers need to know how to build them up in a purposeful way. Overarching modelling methods like the MoSim scheme (Günther & Velten, 2014) or the method for functional modelling by Ullmann and Scalice (2021) exist, however, they mostly aim at quantitative, computer-based models and give little support for qualitative modelling.

When no modelling method is present, design engineers can learn about a qualitative model and its modelling possibilities through textbook descriptions, application examples and conferences as well as workshops or training courses. These learning possibilities are mostly present for models with wide application area, like the Design Structure Matrices (Eppinger & Browning, 2012) for modelling of general interactions in arbitrary systems, or Bond Graphs (Gawthrop & Bevan, 2007) for modelling of relations in technical systems. These models are developed by large communities from different engineering and business areas.

For models in embodiment design that address more specific tasks than DSM or bond graphs, fewer resources are present for support in modelling, leading to increased difficulties in learning them. One of these specific tasks is qualitative system analysis, where the aim lies in the gain of system understanding. Examples of models applicable for this task are the Characteristics Properties Modelling (CPM) (Weber, 2005, 2014), the Contact and Channel Approach (C&C²-Approach) (Albers & Matthiesen, 2002; Matthiesen, 2021) or the working space model (Beetz, Schlemmer, Kloberdanz, & Kirchner, 2017).

The usefulness of these qualitative models in qualitative system analysis is demonstrated through application in industrial projects. Up to now, models are developed and published, mostly with industrial examples (compare for example (Malmiry, Dantan, Pailhès, & Antoine, 2016)), which are valuable to show the application potential of the model. However, modelling methods and training support are mostly missing. This might be a reason why qualitative models are seldom used in an industrial context, as Erbe (2018) states at the example of the CPM.

Another indicator of missing modelling support is shown through an investigation of the C&C²-Approach. Even though a modelling method exists, this approach is mostly used by or with the support of modelling experts from the institutes that developed them (Grauberger et al., 2020). As this contribution deals with the modelling support based on the C&C²-Approach, a more detailed description of it is given in Section 1.1.

An experimental study shows the increase of system understanding through the C&C²-Approach at the example of failure mode and effects analysis (FMEA) (Gladysz & Albers, 2018). This experiment was conducted using models that were previously built up by modelling experts and showed a higher success in applying the FMEA. However, the models were built up before by modelling experts from the institute that developed the C&C²-Approach. The modelling method was not investigated. Therefore no insights regarding its impact are present.

The challenge emerging is, that it remains unclear, whether the modelling method impacts the system understanding of design engineers that are no experts regarding the C&C²-Approach.

An impact of the modelling method regarding the gain of system understanding is crucial for successful model usage of design engineers not familiar with the modelling approach. The aim of this paper is therefore to investigate the impact of modelling with the C&C²-Approach on system understanding compared to intuitive approaches. The hypothesis derived from this aim is formulated as follows:

Qualitative modelling with the C&C²-Approach supports the gain of qualitative understanding of technical systems.

System understanding can be measured on different levels. Eckert, Alink, Ruckpaul, and Albers (2011) describe five levels of function description from the overarching system level to detailed system behaviour derived from details of the embodiment. For this investigation, the hypothesis is divided into three sub-hypotheses. The first sub-hypothesis considers a general understanding of **how** a system behaves, correlating with the first two levels of Eckert et al. (2011) and referred to as *system level* in the following.

Sub-hypothesis H1: Qualitative modelling with the C&C²-Approach increases the gain of qualitative understanding on the system level of technical systems.

The second and third sub-hypotheses consider the details of the design. They investigate the questions, **when** and **where** which details of the embodiment influence the system behaviour. This correlates to the levels three to five of Eckert et al. (2011) and is referred to as the *detail level*. The hypotheses are as follows:

Sub-hypothesis H2: Qualitative modelling with the C&C²-Approach increases the amount of identified function-relevant states of the system.

Sub-hypothesis H3: Qualitative modelling with the C&C²-Approach increases the amount of identified function-critical areas of the system.

To investigate these hypotheses, an experimental study is conducted. Experimental studies are the only studies that allow causal statements about the investigated issue (Hussy, Schreier, & Echterhoff, 2013). In design research, experiments are difficult to conduct, as they need laboratory study setups with a controlled environment. The complexity of the real-life method environment has to be reduced significantly. The implementation of practice-relevant tasks in a laboratory environment for experimental investigations requires elaborate pre-studies to ensure that the aspects of the study work as intended before the experiment is conducted. A more detailed analysis of possibilities for method validation is described in Section 1.2.

1.1 The Contact and Channel Approach

For easier understanding of this contribution, a detailed description of the C&C²-Approach is given. This section is based on Matthiesen, Grauberger, and Schrempp (2019). Parts of the following text are taken from that paper without changes.

The C&C²-Approach is a thinking tool for embodiment design. It aims to support design engineers in recognizing function-related parameters of the embodiment.

As a meta-model it contains elements and rules to build up explicit C&C²-Models. It consists of three key elements and three basic hypotheses that define the usage of its key elements. An overview of the three key elements Working Surface Pair (WSP), Channel and Support Structure (CSS) and Connector (C) is depicted in Figure 1 (left side). A WSP describes the interface where parts of the system connect while it fulfils its function. The CSS goes through system parts and connects the WSP. A CSS can include parts of components or whole subsystems depending on the modelling purpose. The Cs represent a model of the surrounding systems and transmit influences from outside the system boundaries into the system (Gladysz & Albers, 2018). The basic hypotheses describe the possibilities and boundaries of the modelling with the C&C²-Approach. They are depicted in Figure 1 (right side).

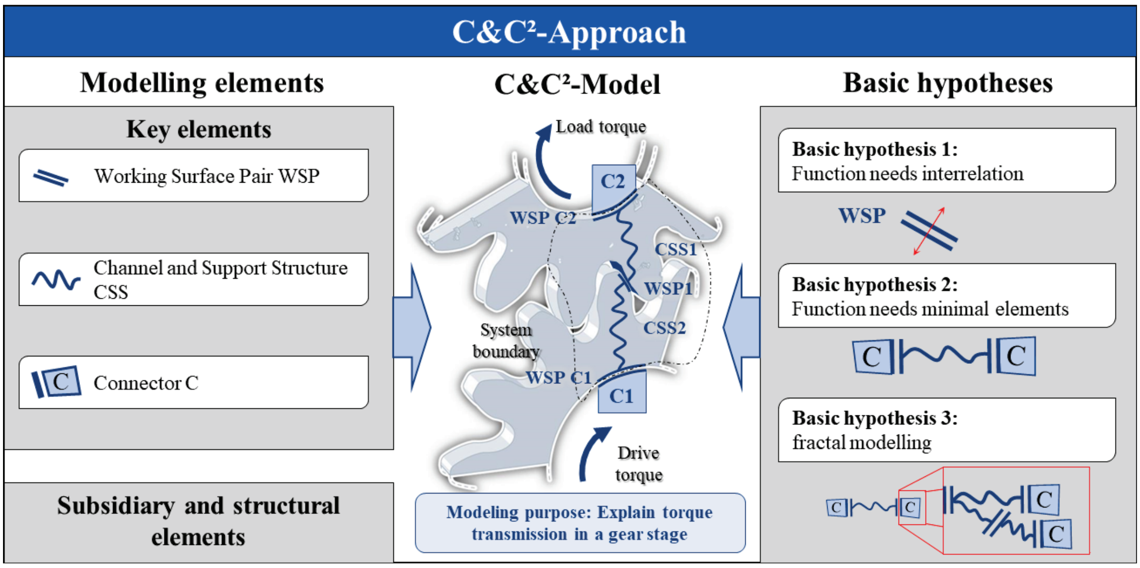


Figure 1: The C&C²-Approach according to (Matthiesen, Grauberger, Sturm, & Steck, 2018)

A C&C²-Model (Figure 1, centre) is derived by using the key elements and basic hypotheses. For modelling state-dependent embodiment-function-relations, the C&C²-Sequence model is used, where the created C&C²-Models are structured according to their temporal sequence and also different levels of detail can be considered. (Matthiesen et al., 2019)

A modelling method was derived almost two decades after the model was introduced. This indicates that the need for modelling method might often not be considered by the model's developers, especially if the model itself seems lean and easy to use. This method differentiates the modelling according to the activities in embodiment design that are addressed. In the activity of analysis, a seven-step method is described. This method is used in the majority of modelling tasks with the C&C²-Approach. It is therefore in focus of this investigation. The four-step modelling method for synthesis remains for further investigations. Figure 2 shows an overview of the modelling method for analysis.

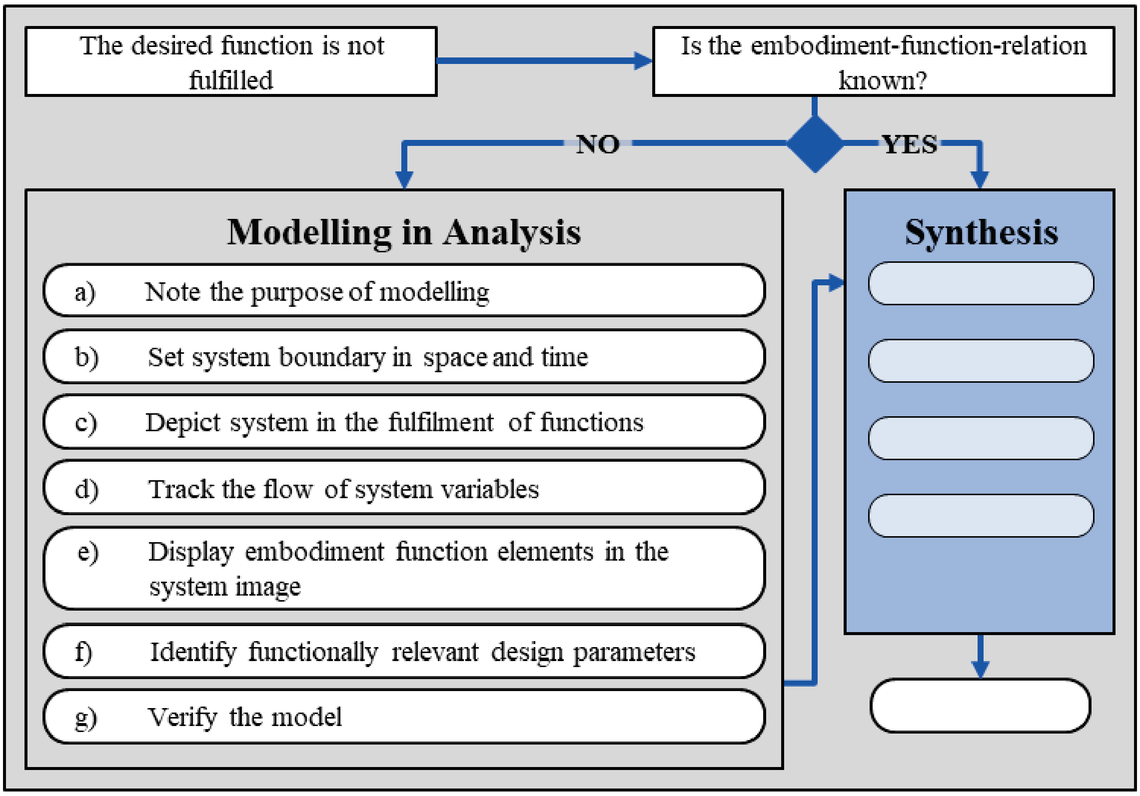


Figure 2: The modelling method of the Contact and Channel Approach translated from Matthiesen, Grauberger, Hölz et al. (2018)

First, the purpose of the model is noted to comprehend the valid scope of this model. Since each model represents only a section of reality, the C&C²-Model is defined in its dimensions of space and time. Then an appropriate depiction of the system is identified, in which the interactions of its components in the function fulfilment are recognizable. All function-relevant energy, material and information flows in the analysed system pass through the embodiment function elements. By tracking the flow of system variables that is done in step d) (Figure 2, centre), unknown embodiment function elements can be identified.

The identified embodiment function elements are integrated into the created representation of the system under consideration of the basic hypotheses. In the next step, functionally relevant embodiment parameters (characteristics and properties) are identified in the embodiment function elements and their relevance for function fulfilment is formulated.

At the end of the modelling, verification of the model is necessary to check whether the model correctly depicts the relations. The model building in the analysis is completed when the embodiment-function-relation is understood sufficiently, i.e., when characteristics in the embodiment are identified and the model is verified. Then a synthesis can be started in which these understood embodiment-function-relations are used to develop an embodiment capable of fulfilling the function.

1.2 Method validation in design research

To investigate the impact of modelling methods, studies are necessary that provide insights about e.g. applicability, usefulness or acceptance of the modelling method. As this is a challenging task, a short overview of challenges and possibilities in method validation in design research is given. This section is based on Eisenmann, Grauberger, Üreten, Krause, and Matthiesen (2021)

The validation of design methods is an essential part of design research, as it is the only way to gain insights into the success criteria of the developed methods (Blessing & Chakrabarti, 2009). The methods in design research are often developed with high effort and validation is carried out afterwards rather for the confirmation of the developed method than for the objective gain of knowledge (Albers et al., 2018).

Insufficient validation is described as a reason why product development researchers fail to identify weaknesses in their methods (Gericke, Eckert, & Stacey, 2017). In case of difficulties in applicability, this can lead to the rejection of a design method in corporate practice (Geis, Bierhals, Schuster, Badke-Schaub, & Birkhofer, 2008). When acceptance barriers, such as high learning effort or abstract method description, occur, the usage of the method is getting more complicated and the effort to benefit ratio of the method increases (Beckmann, Gebhardt, & Krause, 2014; Jänsch, 2007).

Approaches exist that can be used to set up studies for the investigation of modelling methods. On an overarching level, the Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009) contains many aspects of how to validate methods in a laboratory and corporate environment. A process model that addresses experimental validation in methodological research, is the „Concept Map“ according to Üreten et al. (2019). This model considers the experimental validation of methods and provides a structured overview of research-related elements. It is therefore used as a basis for this contribution.

The necessary pre-studies on the modelling method for the C&C²-Approach show, that the prerequisites for an experimental study are met (Eisenmann, Grauberger, & Matthiesen, 2021).

2 Materials and Methods

To gain insights regarding the overarching research hypothesis, an investigation of the sub-hypotheses H1, H2 and H3 is necessary. For this, an experimental study is conducted. In this section, the operationalization of variables for the sub-hypotheses, the study setup and participants are described.

2.1 Operationalization and measurement of variables

The overarching aim of this experimental study is to investigate the support the gain of qualitative understanding of technical systems. The independent variable for all three hypotheses is the video-based training as support in modelling with the C&C²-Approach. The dependent variable is system understanding on different levels of detail. The necessary operationalization of the dependent variable is done by deriving measurable variables for the understanding of technical systems on the different levels of the hypotheses H1, H2 and H3. An overview is shown in Figure 3.

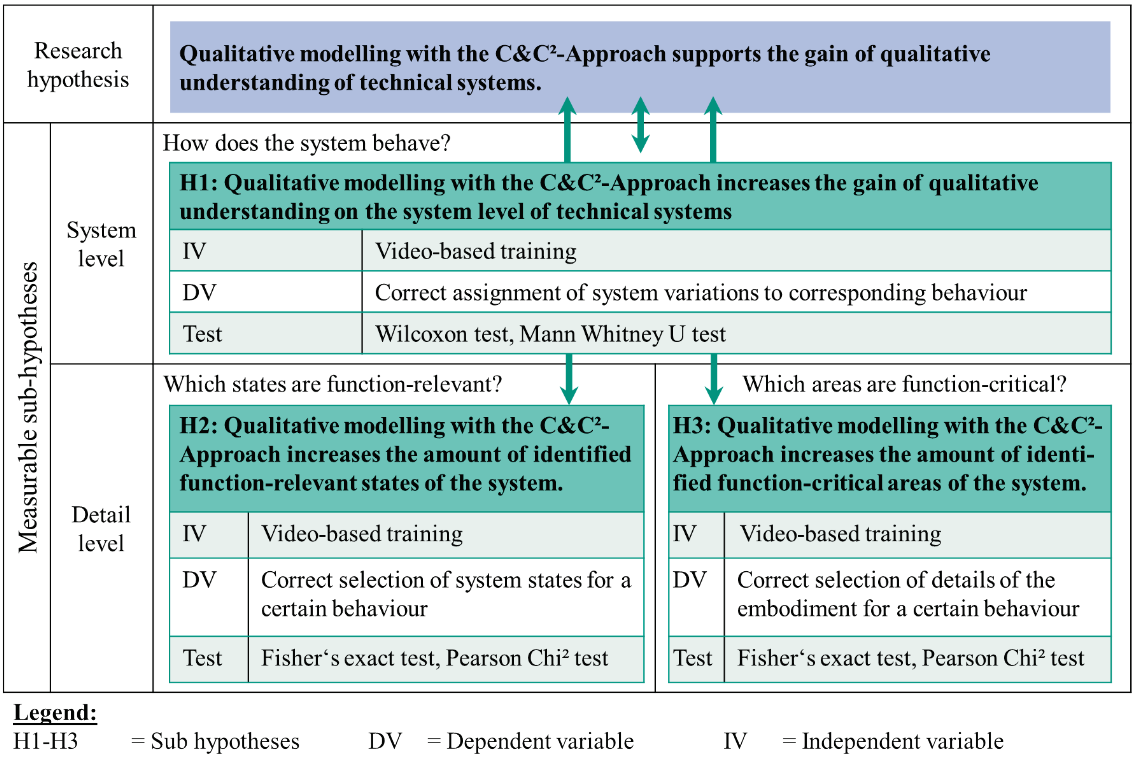


Figure 3: Overview of the research hypotheses, variables and applicable test statistics for the experimental method validation study

On the *system level*, the operationalization is done by assigning correct behaviour to a given system design. It is measured, whether the participants are able to understand how the system might behave based on a given embodiment during a defined operation mode. It is not investigated whether the participants know the detailed cause for the system behaviour. The assignment is done via a comparison of a given variation of the example system with four possible behaviours in single choice answers. No feedback whether the answer was correct, is given. Six tasks are given to each participant, assigning one point for each correct solution. A maximum of six points is possible. The resulting variable is scaled metrical, which allows statistical evaluations using the Mann-Whitney U test or Wilcoxon test.

On the *detail level* of system understanding, the ability to identify function-relevant system states as well as function-critical details of the design causing the predicted behaviour are investigated. This level is operationalized by assigning function-relevant system states and function-critical details of the design. The details of the design are assigned by using an image map of the example system, where areas can be marked that are assumed as critical for the system behaviour. The areas are differentiated into function-critical areas, areas that participate in the function fulfilment and residual structure. The answers are differentiated into whether only the critical areas are marked (correct), if also function-participating areas have been selected (focus too wide) or if also residual structure has been selected. The variable is therefore categorical, allowing statistical evaluation using Fisher's exact test or Pearson Chi² test.

The system states in the detail level are assigned using a multiple-choice questionnaire, where different states can be selected that are assumed as function-relevant. The results are categorized into relevant and non-relevant states, leading to three categories. Only the relevant states are selected (correct), relevant and non-relevant states are selected (focus too wide) and relevant states are missing (partially or both). The variable is therefore also categorical, allowing statistical evaluation using Fisher's exact test or Pearson Chi² test.

2.2 Investigation setup and procedure

In classical experiments, a control group is compared to a test group, which has been treated with the stimulus. This setup generates one data point per participant and allows no conclusions on the abilities of the single participants. These conclusions are especially important in design research, as individual experience and approaches can significantly change the outcome of a design task and besides creativity methods, mostly no preceding experimental studies exist, from which this effect can be estimated.

In extension to the classical arrangement, experimental studies can also be carried out as a crossover design. This study design enables reliable findings with fewer participants, as each participant is placed in both the test and control group. This reduces the person-related variance, as the experience and approaches taken influence both data points generated. With a suitable layout, comparisons can be made within a group as well as between the control and test group, which allows a more in-depth analysis of the gained data. Disadvantages are carry-over and order effects, which may influence the results (Mills et al. 2009). Crossover designs are also difficult for the investigation of long-term effects of the stimulus (e.g. vaccinations).

As a long-term effect of the stimulus is expected, the setting of a classical experiment is chosen. However, as the influence of the individual experience is deemed important to know, each participant is put once in the control group and once in the test group. The control group precedes the test group due to the long-term effect of the stimulus. No feedback is provided in the control group tasks and different systems are used in the control group and test group. Therefore the learning effect is limited to a quicker grasp of what is to do. This is not deemed critical, as there is enough time provided for all participants to finish their tasks. The chosen study design can therefore be seen as a classical experiment with double usage of the participants.

For the selected study design, two systems are required (one in the control group and one in the test group) in which the tasks are carried out. For this purpose, technical systems of manageable complexity are selected that contain challenging embodiment function relations. In the tasks of the study, a snap fit joint and a cartridge press feeding mechanism are used. These systems are known to the participants from everyday life, however, their details challenge even experts in embodiment design, which has been confirmed in previous training sessions.

For reproducibility, the whole study is set up as an online course using the ILIAS platform of the Karlsruhe Institute of Technology. It is conducted using Microsoft Teams and takes about 2h. The teaching part is given via pre-recorded video to avoid influences from the study conductors. The overview of this study design is depicted in Figure 4. The participants are divided randomly into two equally sized groups A and B, which are assigned to different channels in Microsoft Teams. The tasks in the control and test group contain the system level investigation and subsequently the two detail level investigations. The technical systems and tasks shown in the overview are explained in detail in the following section.

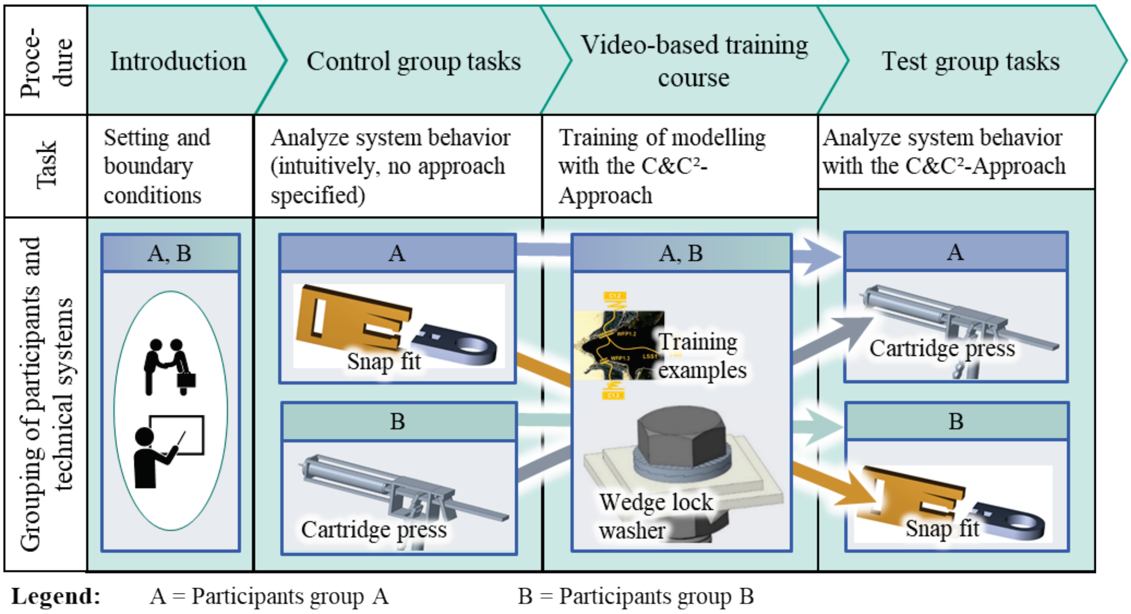


Figure 4: Structure of the experimental validation study with depictions of the systems used in the control and test group as well as in the video-based training course

The study starts with an introductory task in which the focus is set to the observation of design details. The goal of this task is to reduce failures resulting from a misunderstanding of the task focus. Then the control group tasks are done separately for the two groups A and B. Afterwards, a training unit with a modelling task takes place. Then, the test group tasks are conducted by switching the systems from group A and B. The tasks are similar to the control group except for the modelling steps ensuring the application of the modelling method.

2.2.1 System level – investigation of the behaviour

At the beginning of the control group task, the two groups evaluate the system behaviour of six different variants of the snap fit joint (group A) or the cartridge press feeding mechanism (group B). These variants differ in their details of the design. In this step no methodical support is given, the participants proceed intuitively. Figure 5 provides an overview of the tasks at the example of a variant of the snap fit joint.

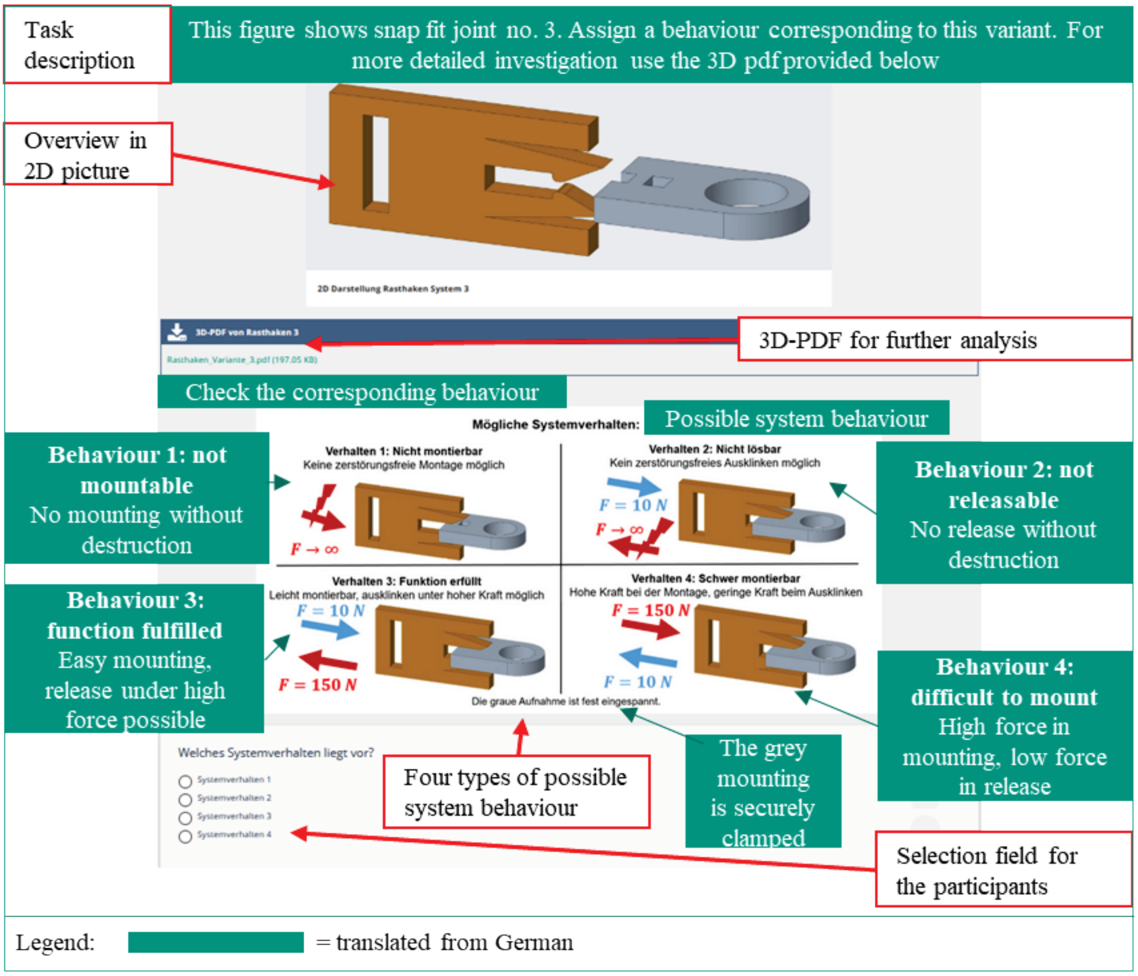


Figure 5: Example of one of the six tasks from the snap fit joint on the *system level* including task description, behaviour template and selection field

On top of the page, the task description is repeated and a picture of the system variation is given. Below a 3D-PDF is accessible, where details of the design can be investigated if necessary. Then the possible behaviours are described with pictures and force indicators (coloured arrows), as this was deemed the quickest way to understand the behaviour in preceding pilot tests of the tasks. At the bottom, the selection of system behaviour has to be done by the participants. The correct answer gives one point, all others give zero. Therefore in this task, a maximum of six points can be gained. The cartridge press tasks are similar and are shown in Figure 6.

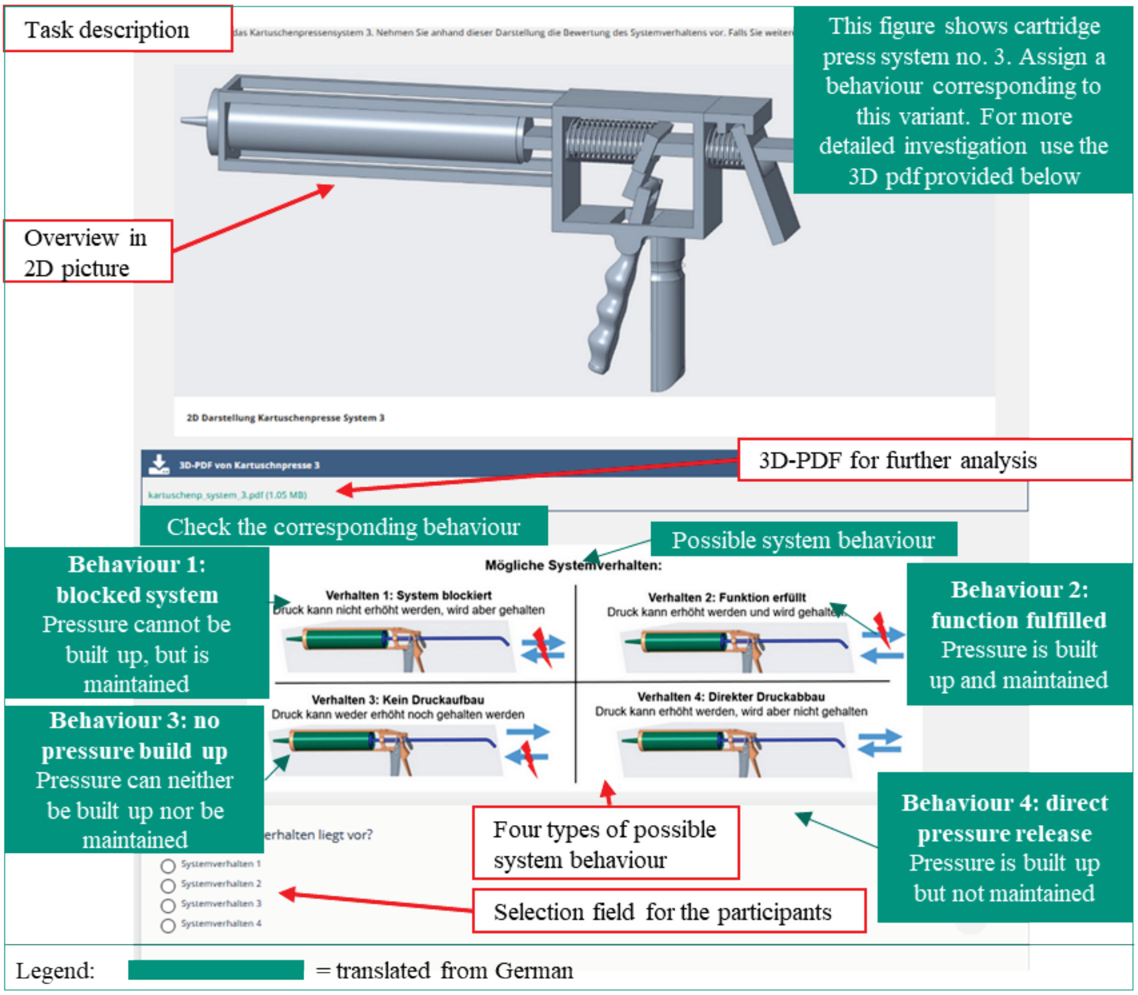


Figure 6: Example of one of the six tasks on the cartridge press on the *system level* including task description, behaviour template and selection field

2.2.2 Detail level – investigation of function-relevant states

Detailed analyses of the system state and details of the design are to be done. They are shown in the overview in Figure 7. For the system states, a multiple-choice questionnaire with 6 possible states for the snap fit and 5 possible states for the cartridge press is provided. For each system, two states are relevant for the desired function.

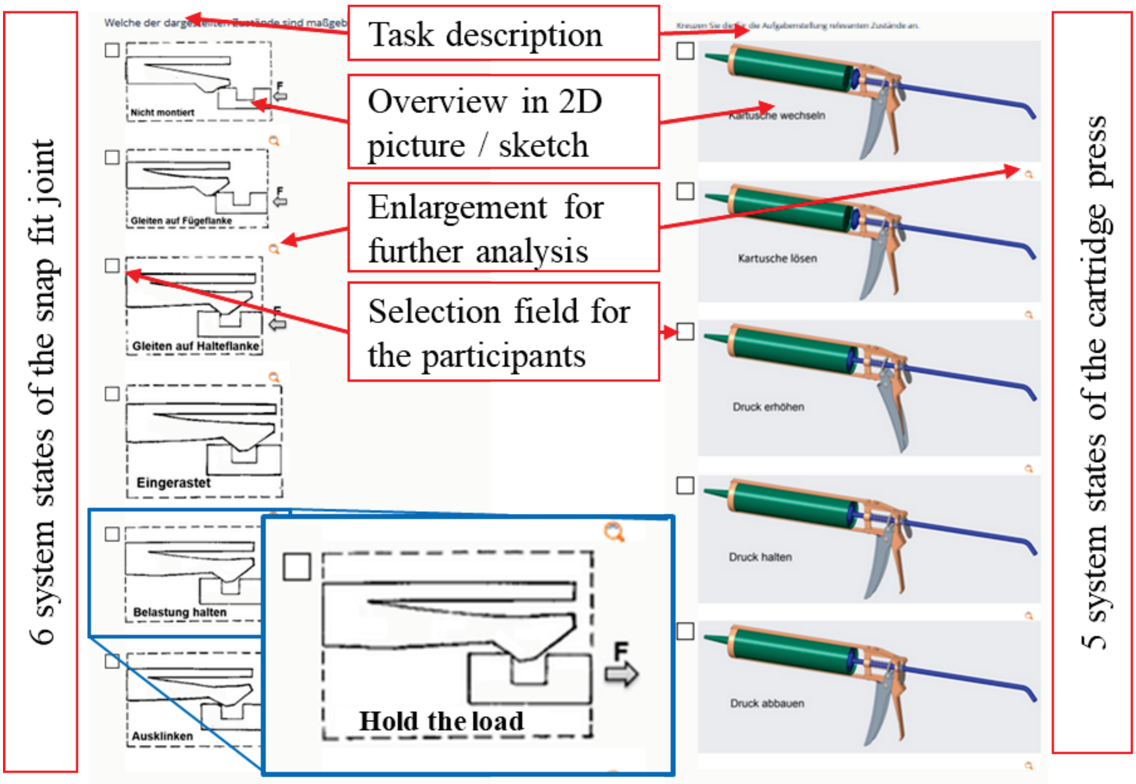


Figure 7: States of the snap fit joint and cartridge press in a multiple-choice task

2.2.3 Detail level – investigation of function-critical details of the embodiment

Subsequently, the function-critical details of the embodiment are investigated using image maps. They are shown in the overview in Figure 8. Here the system image is divided into areas critical for the function, areas that participate in the function and residual structure. Areas critical for the function are defined as areas, where changes in parameter settings have a large impact on function fulfilment. For example, when the angle α in the crucial area at the tip of the snap fit hook (Figure 8, left side) changes by 5°, the mounting force triples, obstructing the function of mounting the snap fit joint. Areas participating in the function are somewhat relevant, e.g. they need to connect the snap fit hook to the mounting device. However, they can be designed more freely without influencing the function. The residual structure is defined as areas that can be removed completely without changing the function.

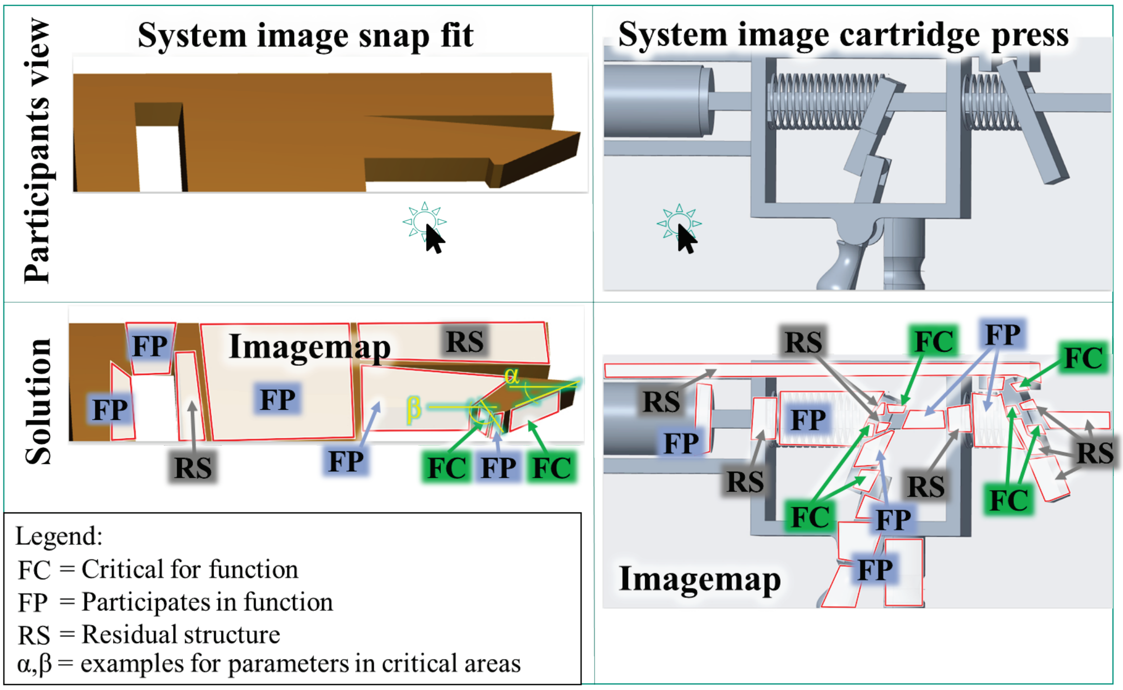


Figure 8: Views of the image maps of the example systems with differentiation of function-critical and function-relevant areas as well as residual structure

2.2.4 *Video-based training as the stimulus*

The *detail level* task of the control group is followed by training in modelling with the C&C²-Approach. Both groups receive this training together as a video recording in a third channel in Microsoft Teams. A two-sided handout is given to accompany the training and later modelling tasks. The training consists of a theoretical part and a guided modelling part (see Figure 9).

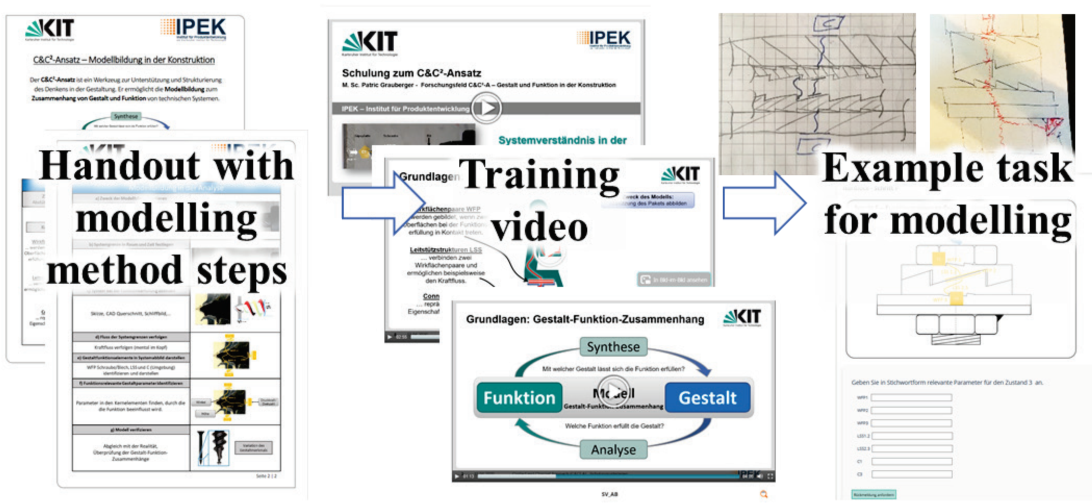


Figure 9: Overview of the training in modelling with the C&C²-Approach

In the theoretical part, the elements of the C&C²-Approach are described at the example of a person carrying a package. Working surface pairs are introduced first as the focus of the modelling. Then the channel and support structures are added and the environmental influences are modelled through the Connectors. The C&C²-Sequence model is also explained in short. The video takes about 5 minutes. Then, the guided modelling part follows, where the participants analyse a wedge lock washer. They are guided through the individual modelling steps of the analysis with the C&C²-Approach (see also Figure 2) and are allowed to take notes in their handouts. At the end of each step, a solution is provided to enable participants to reflect on their solution and to increase the learning effect. During the training unit, communication between the participants permitted to prevent discussions about the control group tasks. For arising questions regarding the training, two modelling experts are present in this Microsoft Teams session.

After the training, the participants are again divided into the two groups A and B. They receive the system that the other group worked on in the control group task. While working on the same task, modelling with the C&C² approach is now used. The participants have to proceed along with the steps of the modelling method, which ensures the usage of the method.

2.3 Participants

In this study, 36 participants without expert knowledge in the C&C²-Approach attended. The participants were recruited from the teaching activities and research network of the institute. The focus lay on choosing homogenous groups regarding their experience in design engineering. It was important that some experience in engineering design was present, as the C&C²-Approach aims at supporting design engineers. However, choosing experts from an industrial background can result in a large scatter regarding the modelling abilities. Therefore, master students and research assistants are chosen as target groups.

The study is carried out in two runs on two different dates using the same online setup. Run 1 is done with 24 students of the master course of Power Tool Design at the IPEK - Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT). These participants already had a theoretical basic knowledge of the C&C²-Approach from lectures in their studies. However, they did not participate in any training on modelling. Therefore it is assumed that their knowledge of the modelling method is not sufficient to apply it in the control group task.

Run 2 is done with 12 research assistants from the pmd at TU Darmstadt. These participants already have more experience in the field of engineering design. They know about the existence of the C&C²-Approach, however, none of them was familiar with the modelling method and its application in tasks of qualitative system analysis.

2.4 Data acquisition and analysis

Initially, outliers of the metric scaled variable of the *system level* investigation are identified and checked. To check whether the sample is normally distributed, the

Kolmogorov-Smirnov test is used. For further analysis, non-parametric tests are chosen due to the assumedly non-existing normal distribution.

For the identification of potential effects from the participant groups, the Mann-Whitney U test for independent samples is conducted. It is checked whether the randomization of sorting participant in groups A and B is valid. The results in the two runs are also compared overall to identify possible significant differences between the students and scientific researchers.

For coupled samples, the Wilcoxon test is used. This applies to the analysis that examines differences between the control and test group, as these are collected from the same participants. For independent samples, the Mann Whitney U test is used. This concerns the consideration of differences in the levels of difficulty of the two systems.

For states and areas of function fulfilment, the Fisher's exact test is used, as the variables are categorical and in some categories, too few data points are collected for using the Pearson Chi²-test. The chosen significance level is $p = 0.05$.

3 Results

In the following section, the results of the experimental study are shown. At first, the results of the investigation of the *system level* are described including the data quality analysis. Thereafter, the *detail level* results are described.

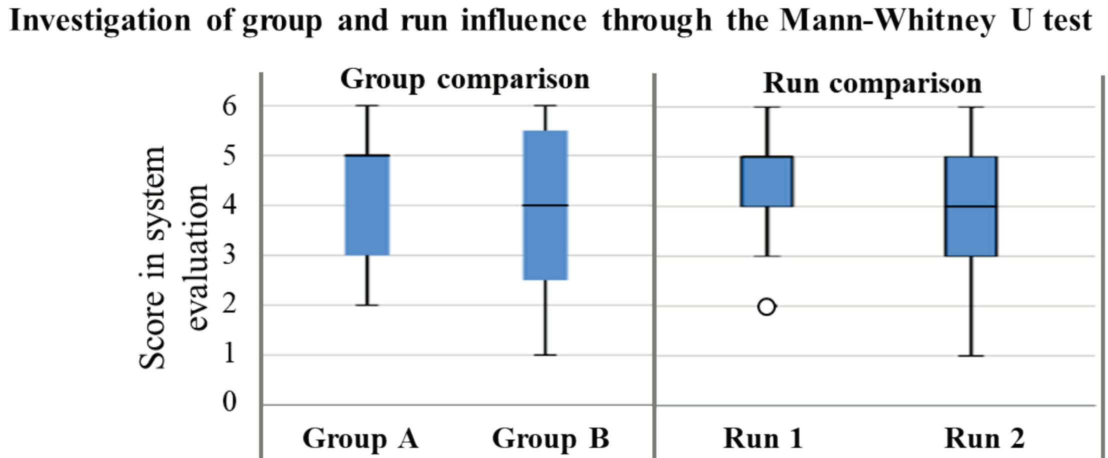
3.1 Investigation on system level

Before the statistical analysis takes place, data quality and boundary conditions have to be checked. To make sure that the available data can be used for the planned analysis, they were checked for outliers by analysing the box plot of the *system level* variable. In this check, one outlier was found. A detailed examination of this data set revealed a note on limited performance for reasons of well-being in the final comment. The data set of this participant (student in the first run) was therefore excluded from the analysis. Consequently, a total of 35 participants (N=35) with two data points each (control and test group) are included in the statistical analyses.

The most important initial data quality analysis is the evaluation, whether the modelling method has been used by the participants. As no software was used for modelling, the participants should sketch the models on paper or in a drawing tool. Indicators for conducted modelling were scans or screenshots from the created models that were collected after the study. The participants were working from home, so the return of created models was not as controllable as in on-site laboratory studies.

30 of the 36 participants delivered drawings of C&C²-Models as evidence. For the six missing models, the working time in the steps of the modelling methods was compared to the other participants. As all of them took some time before proceeding (e.g. 5 to 7 minutes in step c) *depict the system*, see also Section 1.1), it is assumed that they were concerned with the model building even though they might not have finished a model.

In Figure 10, an overview of the investigation of the group and run's influence on the change of system understanding is given. The score in system evaluation represents the correctly rated evaluation by the participants and ranges from 0 to 6.



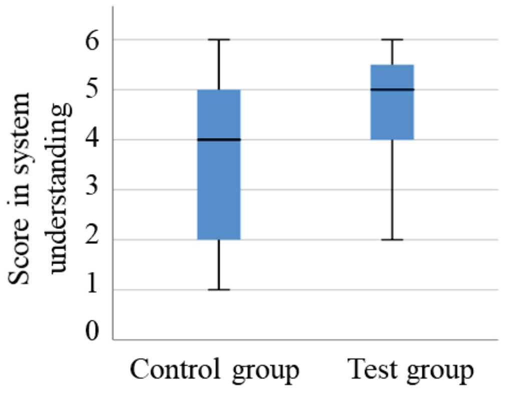
	Group comparison	Run comparison
Mann-Whitney U	590	448
Z	-0,266	-1,322
p	0,791 > 0,05 ➔ no effect r according to Cohen (1988)	0,186 > 0,05 ➔ no effect r according to Cohen (1988)

Figure 10: Analysis of the group and run's influence on the score in the system evaluation (change in systems understanding on system level)

As expected, a comparison of the groups A and B, to which the participants were randomly assigned, shows no significant effect. A comparison of the first run (students with prior theoretical knowledge of the C&C² approach) with the second run (scientific assistants without prior theoretical knowledge of the C&C² approach) also shows no significant effect.

For the investigation of system understanding at the *system level*, the correct assignment of behaviour to a given system design is evaluated here.
The main result of this investigation shows the impact of the modelling method on system understanding. The results of the control group and the test group are compared in Figure 11.

Impact of the modelling method on the system understanding



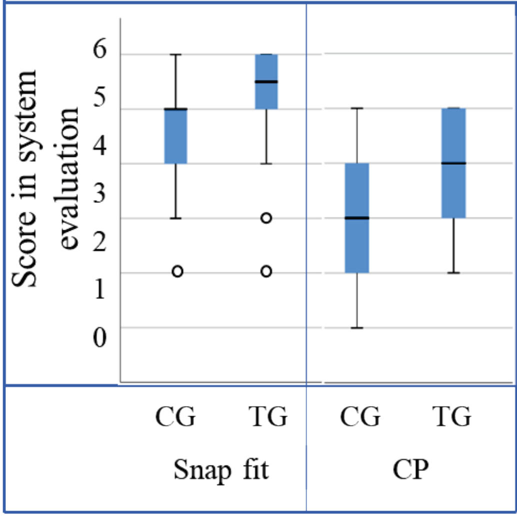
Test statistics – Wilcoxon test	
N	35
Median	Control group: 4,0 Test group: 5,0
Z	-2,223
p	0,026 (< 0,05)
r (Cohen 1988)	0,375 corresponds to a medium to strong effect

Figure 11: Analysis of the impact of the modelling method on the score in the system evaluation

On the left side of Figure 11, the box plot shows the data distribution. On the right side, the results of the Wilcoxon test for the 35 related samples on the impact of the modelling method are shown. Comparing control and test groups, the Wilcoxon test shows a significant difference with a medium to strong effect r according to Cohen (1988). This shows a gain of system understanding on the system level compared to the intuitive approaches used in the control group and therefore indicates approval of the sub hypothesis H1.

A more detailed analysis is conducted to examine the impact of the modelling method on the understanding of each system. For this, a separate consideration of the systems is done. In each case, half of the data is used as an independent sample, since the control and test groups consisted of the other half of the participants. The control group on the snap fit system is therefore the test group on the cartridge press system and vice versa. Figure 12 shows an overview of the results differentiated into the two systems.

System understanding: Comparison of snap fit and cartridge press



Test statistics – Mann Whitney U test		
System	Snap fit	CP
N	35	35
Mann-Whitney U	106	257
Z	-1,640	-2,276
p	0,101	0,023
r (Cohen 1988)	-	0,384

Legend:
CG = Control group TG = Test group
CP = Cartridge press

Figure 12: Analysis of a detailed consideration of each system on its score in the system evaluation (change in systems understanding)

The change in system understanding on the snap fit joint shows a trend in the box plot, however, it is not significant in the Mann Whitney U test. The scores in system understanding are in the upper range of the measuring scale in both the control and test groups. In the cartridge press system, the increase in system understanding shows a significant difference with medium to strong effect r. In summary, the increased gain of system understanding occurs in both systems, therefore the sub-hypothesis H1 is deemed approved. The snap fit joint task results are at the upper end of the evaluation score for both the control and test group, indicating that a slight increase in task difficulty might have led to clearer results.

3.2 Investigation of detail level – critical areas and states

For the investigation of system understanding at the detail level, the correct selection of the function-critical areas as well as the function-relevant states for a system behaviour is evaluated here. Overall, 35 data points could be used for each system. Group A provided 17 participants in the control group of the snap fit connection and the test group of the cartridge press. Group B provided 18 participants for the control group of the cartridge press and the test group of the snap fit connection.
The results of the investigation of function-relevant states are shown in Table 1.

Table 1: Overview of the investigation of detail level regarding function-relevant system states related to sub-hypothesis 2

Selected option		NRS	FRS + NRS	FRS	Statistical analysis		
Explanation		None of the relevant states identified	Correct, but more states than necessary	Correct solution	Fisher exact test	P-value	R (Cohen 1988)
Snap fit connection	Control group	6	10	1	0,527	0,856	-
	Test group	5	12	1			
Cartridge press	Control group	3	11	4	2,392	0,301	-
	Test group	4	6	7			

Legend: NRS = Non-relevant states FRS = Function-relevant states

The raw data show that roughly 3/4 of the participants selected the relevant states in both technical systems (FRS and FRS+NRS). At the snap fit joint, almost all participants selected additional non-relevant states. In the raw data, no trend between the results of the control and test group is discernible. For the cartridge press, there is an increase in the number of participants who selected only relevant states (7 in the test group compared to 4 in the control group). For the statistical evaluation, Fisher's exact test is also chosen, since a boundary condition (<5 data points per cell) of the Pearson-Chi² test is violated Here, both systems show no statistically significant impact of the modelling method on system understanding ($p>0.05$).
Therefore, no evidence has been found to approve sub hypothesis H2.

The distribution of the results for the investigation of critical areas is shown in Table 2.

Table 2: Overview of the investigation of detail level regarding function-critical areas related to sub-hypothesis 3, the majorities of the participants are marked in green (snap fit joint, mostly correct) and red (cartridge press, mostly not correct)

Selected option		Arbitrary + RS	Only FP	FP and FC	Only FC	Statistical analysis		
Explanation		Inadequate system understanding	Missing critical elements	Correct, but focus wider than necessary	Correct solution	Fisher's exact test	P-value	R (Cohen 1988)
Snap fit joint	Control group	0	0	5	12	5,590	0,082	-
	Test group	2	1	9	6			
Cartridge press	Control group	5	13	0	0	2,824	0,241	-
	Test group	2	13	0	2			

Legend: RS = Residual structure FP = areas participating in the function
FC = Function-critical areas

The raw data show that the understanding of the critical areas is higher at the snap fit joint with a slight decrease from control to test group (row 1 and 2, green square). The cartridge press as the more complicated system has far more selectable options. Here almost no participant selected the correct solution and most of them missed critical elements (row 3 and 4, red square). A joint evaluation is not conducted due to the variation in the results that hinder the comparability of the systems.

In the statistical analysis, Fisher's exact test is chosen, as a boundary condition (more than 5 data points per cell) of the Pearson-Chi² test is violated. Here, both systems show no statistically significant effect of the modelling method on system understanding on the level of function-critical areas. Therefore, no evidence has been found to approve sub hypothesis H3.

4 Discussion

The research hypothesis *Qualitative modelling with the C&C²-Approach supports the gain of qualitative understanding of technical systems* is partially approved through the investigated sub-hypotheses. The results regarding the sub-hypothesis H1 show that the usage of the modelling method of the C&C²-Approach significantly increases system understanding on the *system level*. The results regarding the sub-hypotheses H2 and H3 show no statistically significant effect on the identification of function-critical areas and function-relevant system states.

These results extend the insights into the impact of the C&C²-Approach on system understanding in embodiment design. Up to now, it was known that the usage of already built up C&C²-Models supports system understanding (Gladysz & Albers, 2018). The usage of already built-up models, however, is only one of the applications of qualitative models in embodiment design. With this investigation, the positive impact of the modelling method itself on system understanding has been shown in comparison to intuitive approaches on the *system level*. This means that the modelling method of the C&C²-Approach taught in the video-based training leads to increased system understanding even if the model builders are no experts in this approach.

In the chosen experimental design, order effects might occur. All participants are assigned first to the control group task and then to the test group task. The assumption behind this setup is that the learnings from the control group task do not influence the test group results. The systems are based on different physical effects (friction cone at the cartridge press and force distribution at the snap fit joint). Therefore learnings from these tasks don't necessarily increase the ability to solve the other task, especially as no feedback on the chosen solutions is given. The joint modelling task in the training course also focuses on other physical effects, here no knowledge about the cartridge press and snap fit joint is gained. Therefore the influence of learning is deemed negligible. However, as the only way to be sure is the replication of the experiment with separated control and test groups, no definite statement can be made.

For the clarity of the gained results, the comparison with intuitive approaches is not optimal, as a wide variety of unknown approaches are used in the control group, some of which might be more successful than others. This variety increases the scatter of the investigation results. However, for this study, no comparable modelling method with already investigated impact on system understanding is present. The diversion of intuitive approaches has also been limited through the selection of the participants from groups with similar education and experience. For future research, the modelling method used in this study can be used as a baseline to compare new or improved modelling methods in embodiment design.

The difficulty of the example systems varies regarding the *system level* task. The snap fit joint reaches the upper boundary of the measurement scale and the data indicates a generally high system understanding. This might reduce the effect of the modelling method, as the control group also gained quite high results, leaving few possibilities for increase. As the more complicated system, the cartridge press did not reach the boundaries of the measurement scales, indicating that this system difficulty is suitable for such a task. To gain more clear effects in future investigations on the *system level*, the system difficulty of the snap fit joint has to be increased. This could be done e.g. through the addition of more components (more complicated system) or through the addition of 3D working surface pairs (more complex system).

On the *detail level* investigation regarding the critical areas, it seems that the snap fit joint was far easier to investigate, as almost all participants identified the critical areas. In the test group, the share of participants that identified additional areas increased. This might be caused by overthinking of the participants in identifying embodiment function elements (steps e) and f) of the modelling method). This shows a potential weakness of the modelling method that should be investigated further. In addition, possibilities for improvements of the measuring precision of the image maps can be derived from the results. The image map of the snap fit joint most likely contained too few choices and the residual structure was seemingly easy to identify. This led to very high scores in the test and control group, blurring out possible effects. Here, a more complicated system could support in more precise results of the investigation.

In the *detail level* investigation of states, almost all participants identified additional states of the snap fit joint as critical states. This indicates a low efficacy of the step b) of the modelling method, where states for the modelling have to be identified. It could also be that the selected states were not clear in their differentiation. Here also a more complicated system with clearer distinctiveness of states could support clearer results. At the cartridge press, more participants identified the correct result in the test group, however, also the completely wrong answer rate was increased. This also indicates a low efficacy of the state identification in the modelling method.

5 Conclusion and Outlook

This contribution investigates the impact of a modelling method based on the Contact and Channel Approach in an experimental study with 35 participants and two technical systems. The impact of the modelling method is investigated in tasks of gain of system understanding on two different levels of detail. It shows that the modelling method based on the Contact and Channel Approach increases understanding of the technical systems on the overarching level of how a system behaves given a certain variation of the details of its embodiment. On the detail level of when and where exactly the function-relevant details lead to the shown behaviour, no statistically significant effect could be identified.

However, especially in the investigation of the detail levels, the potential for further research emerges regarding the efficacy of the modelling method. For example, scarce support is given in the modelling method on how to identify function-relevant system states. The participants did mostly not succeed in this task.

Further research here might also fall back onto the plethora of different C&C²-Models created by the participants. This data might support in-depth analysis of the modelling process and identification of difficulties in the steps of the modelling method.

The developed experimental study design can also be used as a reference for investigations of other modelling methods in embodiment design. The results can lay a baseline for the efficacy in the gain of system understanding by qualitative modelling.

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