Investigating the generation of specific design knowledge: experimental validation of a qualitative modelling method

Patric Grauberger *, Matthias Eisenmann *, Emily Windisch and Sven Matthiesen

IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

ABSTRACT

Specific design knowledge (SDK) plays a crucial role in engineering design, as it enables designers to define a system structure that can fulfil the required functions through its behaviour. A variety of modelling methods aim at supporting the gain of this knowledge. However, they are usually evaluated concerning the designs produced rather than the knowledge generated in the process. Also, established operationalisations of SDK are missing. This results in a lack of understanding of the generation of SDK. Hence, an experimental study is conducted to investigate the impact of an exemplary modelling method on the generation of SDK. The study is set up with 35 participants, who analyse two technical systems. Intuitive approaches are compared with the application of the modelling method. On the system level, SDK is assessed through relations of structure and behaviour. On the detail level, function-critical system areas and function-relevant system states, are investigated. Results show, that the modelling method increases SDK at the system level compared to intuitive approaches. At the detail level, no statement about statistically significant differences could be derived. The presented study design can provide a baseline for investigations of similar modelling methods or other design methods supporting the generation of SDK.

KEYWORDS
Embodiment design; design research; design method validation; experimental study

1. Introduction

Knowledge plays an important role in design as it is central to the creation of artifacts by mapping between required functions and structure fulfilling those functions (Hatchuel and Weil 2009). When engineering designers define technical systems, *specific design knowledge* is necessary (Hubka and Eder 1990). This *specific design knowledge* contains process-related and object related knowledge. Process related knowledge includes theories on design processes and design methods applied to the particular case. Object-related knowledge relates to the technical system under development, i.e. the design artifact. It includes specific

CONTACT Patric Grauberger patric.grauberger@kit.edu IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, Karlsruhe 76131, Germany

*Patric Grauberger and Matthias Eisenmann equally contributed for this article.

aspects of theory on technical systems as well as knowledge of properties of existing or proposed technical systems. (Eder 2011).

To set the focus of the investigation at hand, object-related specific design knowledge is defined here as *specific design artifact knowledge* (*SDAK*). *SDAK* contains all aspects necessary to define a technical system fulfilling a set of required functions. *SDAK* can further be characterised through knowledge of the domains of *function, behaviour* and *structure* of the technical system to be designed (Gero and Kannengiesser 2004) and the ability to reason about these aspects (Johnson and Satchwell 1993). Knowledge of *constraints* concerning function, behaviour and structure as well as on *relationships* between them (Gero and Kannengiesser 2004; Gorti et al. 1998) enable this kind of reasoning. Constraints and relationships often lead to unique requirements on the technical system in the design process, which makes it very challenging to reuse *SDAK* (Busby 1999). Consequently, *SDAK* frequently has to be generated specifically for the individual design case.

In many cases, *SDAK* is part of the experience built up by engineering designers during their work on design projects. However, it is also possible to generate *SDAK* in a more systematic and structured way. For example, C-K design theory provides a framework to build up knowledge in conceptual design processes (Hatchuel and Weil 2009) at a macro level. Weisbrod and Kroll (2018) illustrate, how this framework can be used to systematically support knowledge generation through a design method and validate their method in a follow-up study (Kroll and Weisbrod 2020). The final results of their design method are a requirement list and a final concept to be used for the following detailed design. That means, *SDAK* is generated concerning conceptual aspects but neither on details of structure and behaviour nor on constraints and interrelationships on the detail level.

On the one hand, most of the design methods used to generate *SDAK* remain at a conceptual level as described in Weisbrod and Kroll (2018). On the other hand, there are design methods that are possibly able to support the generation of *SDAK* for detail design. These methods are evaluated through the designs produced rather than the knowledge generated in the process. This results in a lack of understanding and consequently a lack of established design methods to support the generation of *SDAK* in unique cases within the detail design of technical systems. Therefore, this contribution aims to investigate the generation of *SDAK* for detail design by using a design method for knowledge generation through qualitative modelling as an exemplary case.

2. Literature review

In product development, the capability for knowledge generation regarding the modelling of product structures is deemed sufficient (McMahon, Lowe, and Culley 2004), as it can rely on a plethora of available models, for example. Concerning *SDAK* for detail design, appropriate models for knowledge generation should include function, behaviour and structure of a technical system. Through modelling methods, engineering designers can be supported in building up those models. Therefore, section 2.1 reviews the literature on qualitative modelling methods for knowledge generation.

To assess the impact of design methods for modelling, their effects need to be investigated in validation studies, where they are applied by method users. Therefore, Section 2.2

reviews the literature on research methodology for design method validation to identify appropriate research methods.

2.1. Qualitative models and modelling to generate specific design artifact knowledge

In design, modelling processes can be described by using the Function Behaviour Structure Ontology (FBS) by Gero and Kannengiesser (2004). Especially in the *analysis* phase of the FBS, a plethora of models is used. Quantitative models like multibody simulations or models using the finite element method come to mind. In building up these quantitative models in a purposeful way, qualitative assumptions about *SDAK* must be made. Here, besides intuitive approaches like sketching (Serrano Lasa, Etxabe, and Iriondo 2022), qualitative models can support. Often they are used in the structuring of relations and thoughts regarding *SDAK*, like the Characteristics properties models (CPM) (Weber 2014), Design Structure Matrices (DSM) (Eppinger and Browning 2012) or Bond Graphs (Gawthrop and Bevan 2007). For identification of *SDAK*, graphical models like the Contact and Channel Approach ($C\&C^2$-A) (Albers and Matthiesen 2002) or the Organ Domain models (Andreasen, Hansen, and Cash 2015) exist. Summarising studies like Weidmann et al. (2017) or Matthiesen et al. (2019) give a glimpse of the plethora of single case studies that have been published regarding the application of qualitative models in solving corporate design problems. However, even for the widespread models like bond graphs or DSM, the impact of their application is still unclear and hinders further research into the improvement of gaining specific design knowledge by using these models. Modelling training exists, however, mostly no explicit modelling method is present. Summarising, the first steps in the generation of *SDAK* can be supported by qualitative models, however, due to the lack of explicit training methods and reliable evidence regarding their impact, this support remains unclear.

2.2. Research methodology for design method validation

Design methods are one core result of design research and enable knowledge on design to be used in practice (Cross 2007; Blessing and Chakrabarti 2009). As such, design methods should be validated concerning their impact on the designer, the design process and design outcomes. Design methods originate from different positions between theoretical and pragmatic stances (Reich 2010) and include insights from various scientific disciplines (Cross 2007). This results in a lack of clarity as to how design method validation should take place and what kind of evidence is needed for validation (Gericke, Eckert, and Stacey 2017).

As the outcomes of design is influenced by various variables, multiple studies with differing foci are needed to comprehensively validate a design method (Tromp and Hekkert 2016; Blessing and Chakrabarti 2009). Additionally, iterations might be necessary, based on the studies' results (Gericke, Eckert, and Stacey 2017). Studies to validate design methods can be empirical or theoretical in nature and focus on the soundness of the design method itself or its outcomes while being applied (Blessing and Chakrabarti 2009; Pedersen et al. 2000). Existing approaches for design method validation such as the *descriptive study II* within the *DRM – Design Research Methodology* (Blessing and Chakrabarti 2009) and the *validation square* (Pedersen et al. 2000) suggest conducting early investigations of design methods in a controlled environment focusing on *efficacy* (=direct effects of design method application on the designer's behaviour (Daalhuizen and Cash 2021)). Other researchers suggest utilising scientific practice from other disciplines such as medicine (Frey and Dym 2006) or the social sciences (Bender et al. 2002) to study direct design method effects. In those disciplines, the direct effects of treatments on participant behaviour are operationalised into observable variables and investigated in human subject experiments. Hence, in the case of a lack of clarity as to the direct effects of a design method, experimental studies focussing on *efficacy* in a controlled environment seem to be a suitable research design for validation.

To investigate the direct effects of design method application in a controlled context, the desired effects need to be operationalised into variables to be made accessible for assessment. An overview of the current research practice of design method validation (Eisenmann et al. 2021) shows that the majority of researchers develop individual operationalisations which are suitable for their own design method only. This results in a lack of comparable operationalisations and research methods to assess them. Rigorous *small scale scoping studies* (Cash et al. 2012) in *theory building mode* (Cash et al. 2022) can be used to develop new operationalisations to enable an analysis of underlying core mechanisms of design methods.

Summing up, design methods for modelling are potentially suitable to support the generation of *SDAK* for detail design. For reliable statements regarding their effects on *SDAK*, these modelling methods need to be investigated in validation experiments focusing on *efficacy* within a controlled environment.

3. Research objectives and hypotheses

The objective of this paper is to investigate the influence of qualitative modelling on the generation of *SDAK* for detail design. In the case at hand, an established operationalisation to assess *SDAK* for detail design is missing. Hence, an experimental scoping study is conducted using a newly developed operationalisation to identify the effects of modelling on *SDAK* for detail design. We, therefore, conclude with the following research question to be answered through the investigation:

> RQ: How does qualitative modelling influence the generation of *specific design artifact knowledge* for detail design?

The research question is addressed by studying the effects of qualitative modelling with the *Contact and Channel Approach (C&C^2 A)* as an exemplary case. Additionally, underlying core mechanisms of knowledge generation are explored. This is done by structuring *SDAK* for detail design in knowledge on the *system level* and *detail level* (see operationalisation presented in Section 4.3). Knowledge on the *system level* representing the ability to reason about relations of the *structure* and *behaviour* of the technical system respective to its *function* (compare Section 1) results in the first hypothesis to be tested in the experiment:

> H1: Qualitative modelling using C&C^2-A positively influences *SDAK* for detail design on a system level.

Knowledge on the detail level relates to the *states* (=detail behaviour) and *areas of embodiment* (=detail structure) of the technical system which are critical to fulfilling its *function*. Hence, the derived additional hypotheses to be tested to investigate knowledge on the detail level are:

H2.1: Qualitative modelling using C&C^2-A positively influences *SDAK* for detail design relating to function-relevant *states* of the technical system.

H2.2: Qualitative modelling using C&C^2-A positively influences *SDAK* for detail design relating to function-relevant *areas of embodiment* of the technical system.

4. Materials and methods

4.1. *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 (Eisenmann et al. 2021), 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 participant-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 for 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 the long-term effects of the stimulus (e.g. vaccinations).

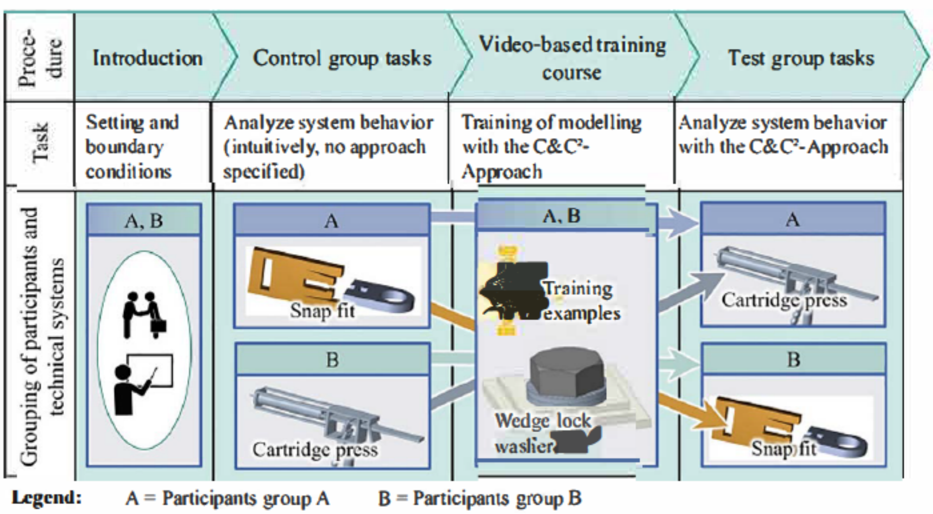


Figure 1. Structure of the experimental validation study with depictions of the systems used in the control and test group as well as in the video-based training course.

Table 1. Overview of the participants and runs in the study.

Run	Group	Control group system	Test group system
Run 1, master course students	A: 12 participants	Snap-fit connection	Cartridge press
	B: 12 participants	Cartridge press	Snap-fit connection
Run 2, research assistants	A: 6 participants	Snap-fit connection	Cartridge press
	B: 6 participants	Cartridge press	Snap-fit connection

As a long-term effect of the stimulus is expected, the setting of an experimental design 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 (see also Figure 1). 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 an 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 that can be analysed under the given boundary conditions of participant knowledge, time and supplemental materials. 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 University of the Authors' institute. 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 general overview of this study design is depicted in Figure 1. 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. The participants and their allocation to the general study design is shown in Table 1.

The study starts with an introductory task in which the focus is set on 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 groups A and B. The tasks are similar to the control group except for the modelling steps ensuring the application of the modelling method.

4.2. *Participants*

In this study, 36 participants without expert knowledge in the C&C^2-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. Some experience in engineering design needed to be present, as the C&C^2-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 authors' institute. These participants already had a theoretical basic knowledge of the C&C^2-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 a chair of product development of another German university. These participants already have more experience in the field of engineering design. They know about the existence of the C&C^2-Approach, however, none of them was familiar with the modelling method and its application in tasks of qualitative system analysis.

4.3. *Operationalisation and data acquisition*

This section deals with the operationalisation of *SDAK* on the system and detail level. Johnson and Satchwell (1993, 80) define 'technical system understanding' as

> the ability to use system knowledge in a meaningful way and reason qualitatively about three aspects of the system: a) the structure of the system, b) the function of the components within the system and c) the behavior of those components as they interact with other components in the system.

In this study, we rely on this definition as a starting point to operationalise *SDAK* for detail design.

The independent variable for all three hypotheses is the video-based training as support in modelling with the C&C^2-Approach. It can be adjusted to 1 (video-based training for the participants) or 0 (no training for the participants). The aim of the task representing the dependent variable is *SDAK* for detail design on different levels of detail. The necessary operationalisation of the dependent variable is done by deriving measurable variables relating to the hypotheses H1, H2.1 and H2.2. An overview is shown in Figure 2.

As no software is used for modelling, the participants are asked to sketch the models on paper or in a drawing tool. Indicators for conducted modelling are scans or screenshots from the created models that are collected after the study. The participants are working from home, so the return of created models is not as controllable as in on-site laboratory studies.

On the *system level*, the operationalisation is done by assigning correct behaviour to a given system design (= overall structure). It is measured, whether the participants can 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 on 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

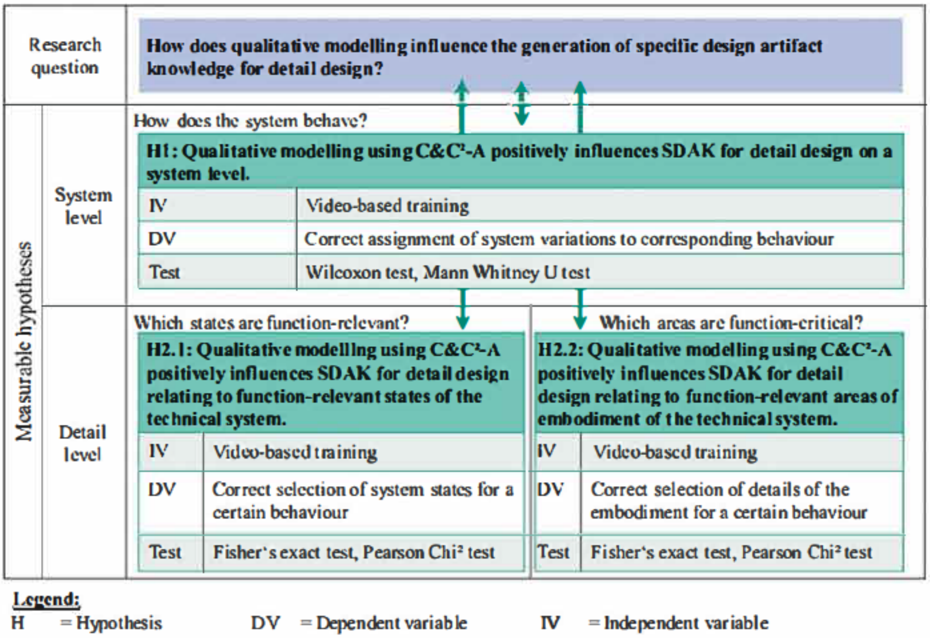


Figure 2. Overview of the research question and hypotheses, variables and applicable test statistics for the experimental method validation study.

resulting dependent 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 areas of the design causing the predicted behaviour are investigated. This level is operationalised by assigning function-relevant system states and function-critical areas 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 Chi^2 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 categorised 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 Chi^2 test.

In defining these observable variables, care was taken to ensure that they can also be used independently of qualitative models and modelling in design to capture *SDAK*. In this way, these variables can be used to investigate design methods that address *SDAK*.

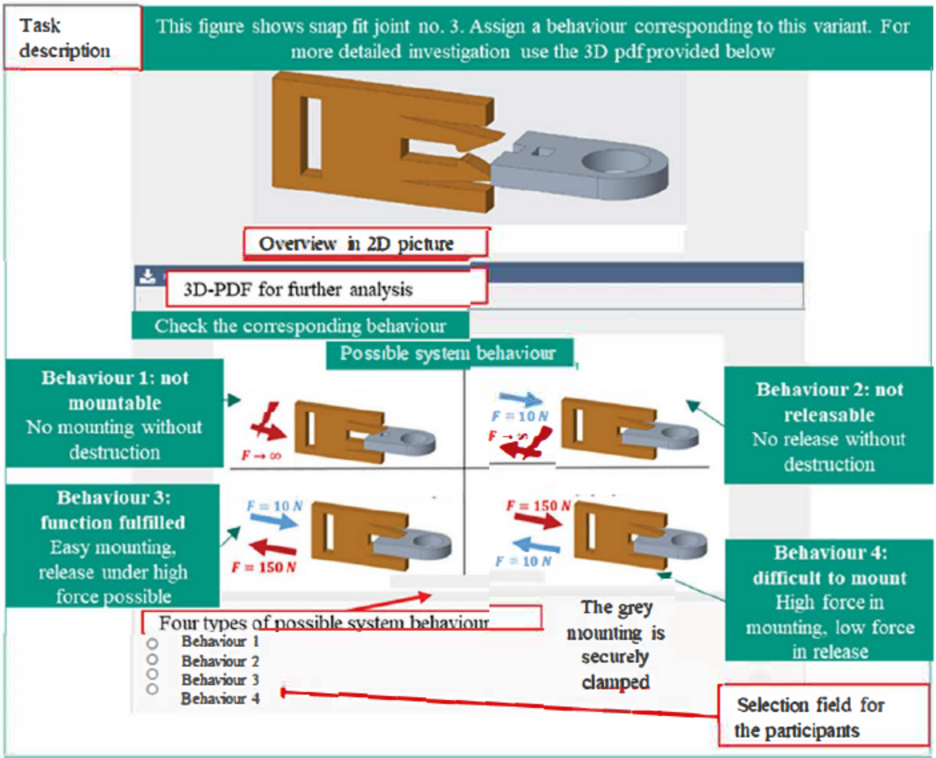


Figure 3. Example of one of the six tasks from the snap fit joint on the *system level* including task description, behaviour template and selection field.

4.3.1. *Realisation of assessment on the system level*

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 3 provides an overview of the tasks at the example of a variant of the snap fit joint.

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 4.

4.3.2. Realisation of assessment on the detail level – 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 5. 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.

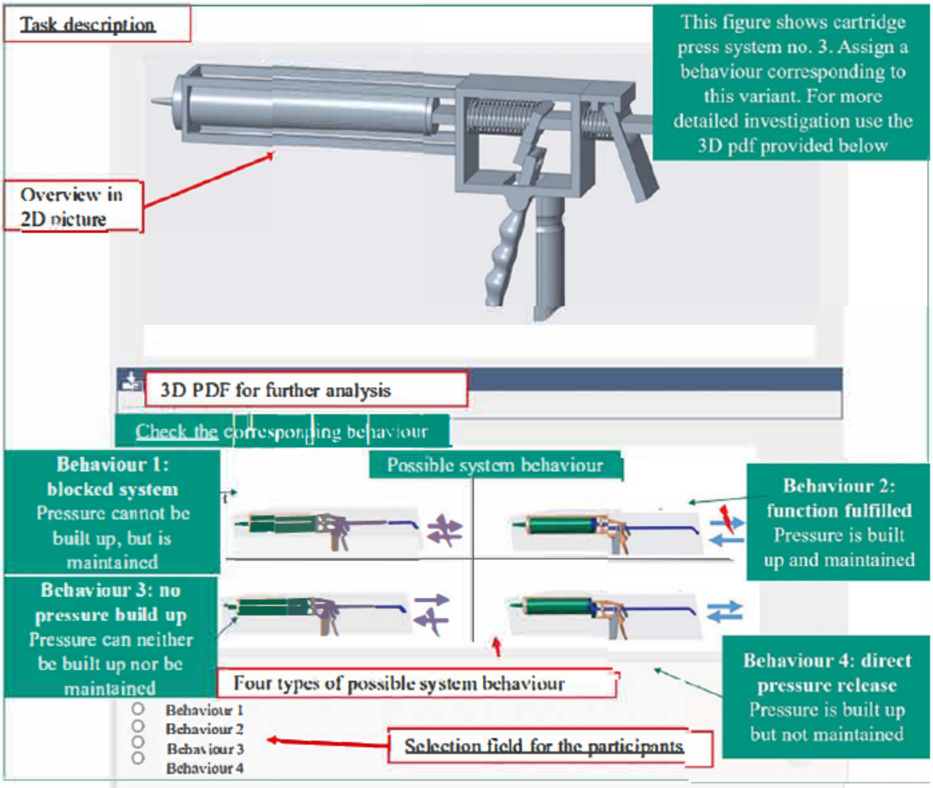


Figure 4. Example of one of the six tasks on the cartridge press on the *system level* including task description, behaviour template and selection field.

4.3.3. Realisation of assessment on the detail level function-critical areas of the embodiment

Subsequently, the function-critical details of the embodiment are investigated using image maps. They are shown in the overview in Figure 6. 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 6, 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, for example 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.

4.3.4. Video-based training of the modelling method

The *detail level* task of the control group is followed by training in modelling with the C&C^2-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

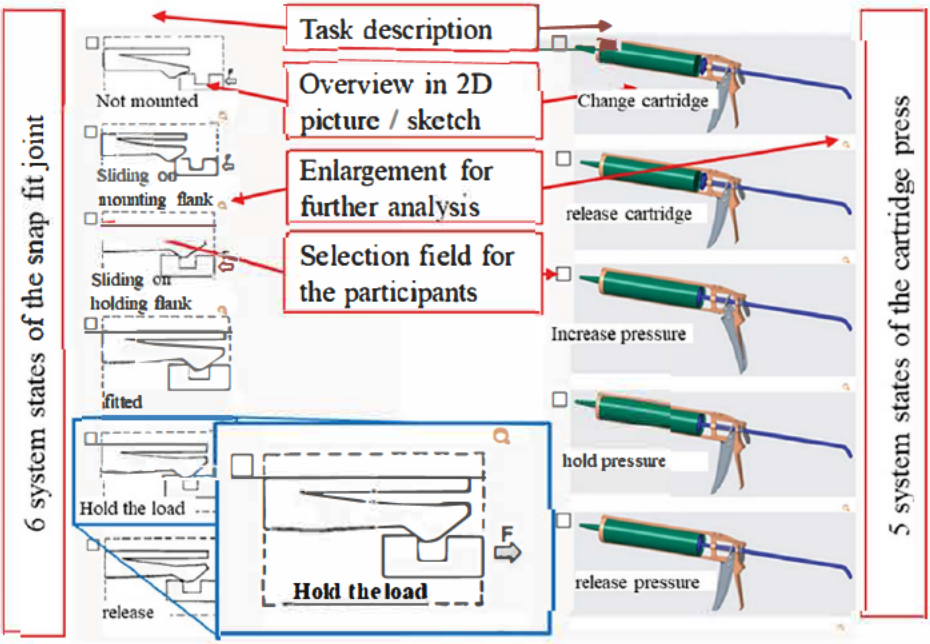


Figure 5. States of the snap fit joint and cartridge press in a multiple-choice task.

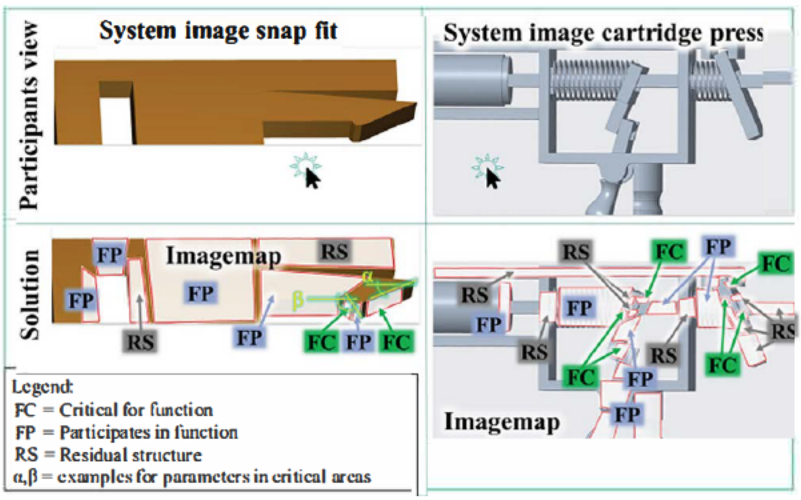


Figure 6. Views of the image maps of the example systems with differentiation of function-critical and function-relevant areas as well as residual structure.

later modelling tasks. The training consists of a theoretical part and a guided modelling part (see Figure 7). This modelling training was developed previously from an engineering training course (Grauberger et al. 2021). This training course aimed at teaching of the C&C^2-Approach for design engineers and was adapted for application in experimental studies of method validation by analysing the method steps and elements of teaching.

Figure 7. Overview of the training in modelling with the C&C²-Approach.

These elements were clustered using Bloom's taxonomy (Bloom 1956) to identify difficulties. It was shown that the levels (remember, understand, apply, analyse, evaluate, create) did not build up onto one another and gaps are shown. The course was then optimised by applying factors from the up to now largest meta-analysis on learning success (Hattie 2010). These factors addressed e.g. visualisation (confusing graphics in training) or didactic structure (no in-between feedback). The applicability was investigated before it was applied in this study (Eisenmann, Grauberger, and Matthiesen 2021).

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 recognising 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 8 (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 and Albers 2018). The basic hypotheses describe the possibilities and boundaries of the modelling with the C&C²-Approach. They are depicted in Figure 8 (right side).

A C&C²-Model (Figure 8, 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, Grauberger, and Schrempp 2019).

In the theoretical part, the three key elements of the C&C²-Approach are described at the example of a person carrying a package. Working surface pairs (WSPs) are introduced first as the focus of the modelling. They connect components or subsystems that interact

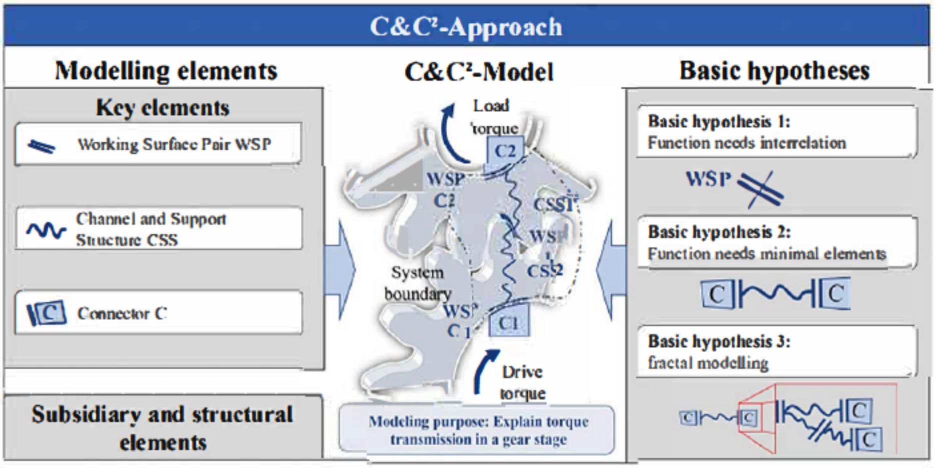


Figure 8. The C&C²-Approach according to Matthiesen et al. (2018b).

during function fulfilment and are depicted as a double-line in the systems depiction. Then the channel and support structures are added, that connect the WSPs and are depicted as a curved line. The environmental influences are modelled through the Connectors, that are depicted as polygonal boxes. An example of the key elements in a C&C²-model is shown in Figure 13. 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 modelling method for analysis with the C&C²-Approach and are allowed to take notes in their handouts. Figure 9 shows an overview of the modelling method for analysis.

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.

In the second step, the states of the system, in which modelling might be purposeful, have to be selected. The selection possibilities are shown in Figure 10. After the selection, state 3 is presented as solution and explained. Only in this state, the behaviour of interest takes place.

Thereafter, the boundaries regarding space are selected as well. Here, the solution is presented as well, even though it is not as harsh a criterion as with the states. A boundary defined too wide (right side) complicates the modelling, while a boundary too small leaves important elements out (Figure 11).

Then an appropriate depiction of the system is identified, in which the interactions of its components in the function fulfilment are recognisable. The task and a side-view as possible solution are shown in Figure 12.

In this sketch, all function-relevant energy, material and information flows in the analysed system pass through the key elements. By tracking the flow of system variables that is done in step d) (Figure 9, centre), unknown key elements can be identified. The identified key elements are integrated into the created representation of the system under consideration of the basic hypotheses. The task and sample solution are shown in Figure 13.

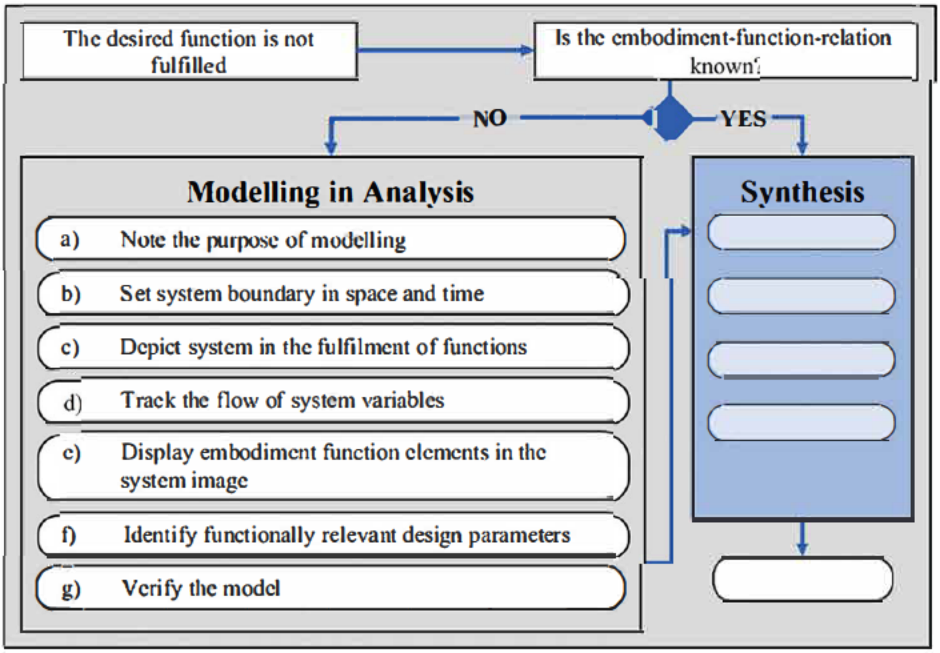


Figure 9. The modelling method of the Contact and Channel Approach translated from Matthiesen et al. (2018a).

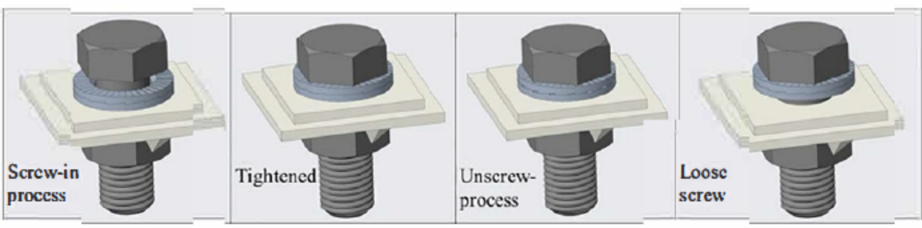


Figure 10. States for selection in the modelling training.

In the next step, functionally relevant embodiment parameters (characteristics and properties) are identified in the key elements and their relevance for function fulfilment is formulated. A possible solution is given, where parameters and their relevance for the system behaviour are explained. This step is shown in Figure 14.

At the end of the modelling, verification of the model is necessary to check whether the built-up model correctly depicts the relations. This step is not investigated in the study, as the focus lies in modelling and not verification of knowledge.

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&C^2 approach is now used. The participants have to

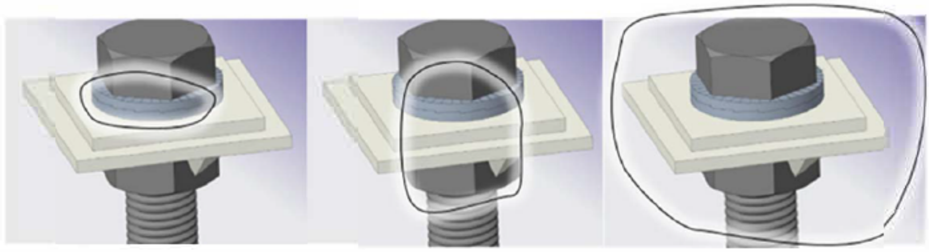


Figure 11. System boundaries for selection in the modelling training.

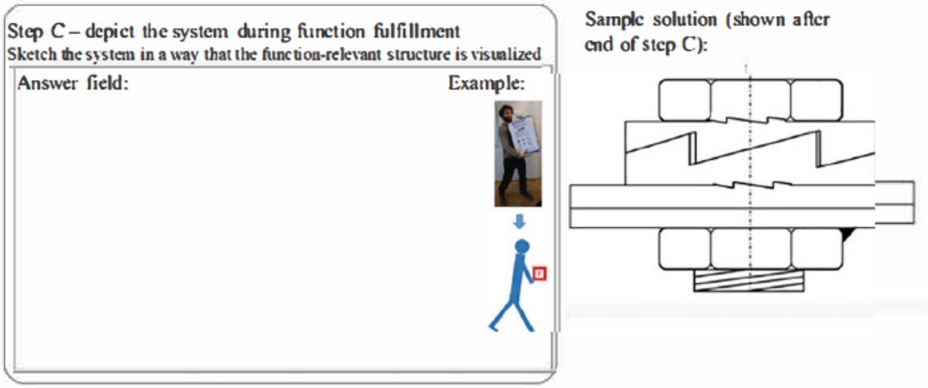


Figure 12. Sketch of the system in modelling training.

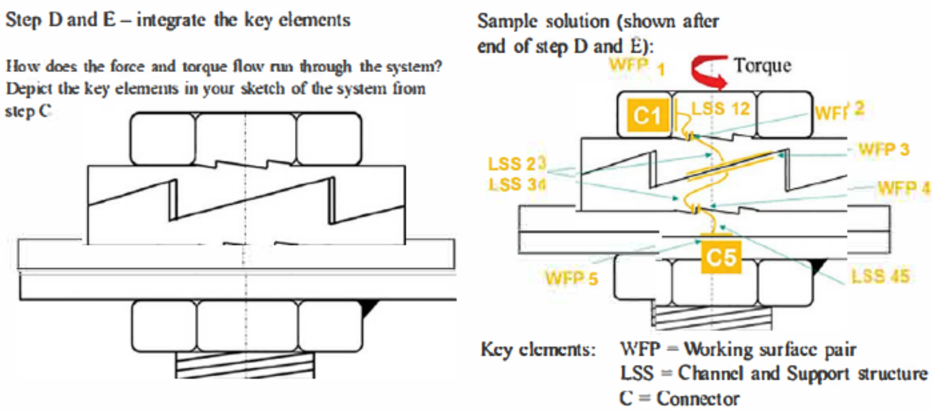


Figure 13. Integration of the key elements in the modelling training.

proceed along with the steps of the modelling method, which ensures the usage of the method.

4.4. Data analysis

The statistical evaluation follows recommendations by statistic text books, e.g. Witte and Witte (2017) depending on the generated data.

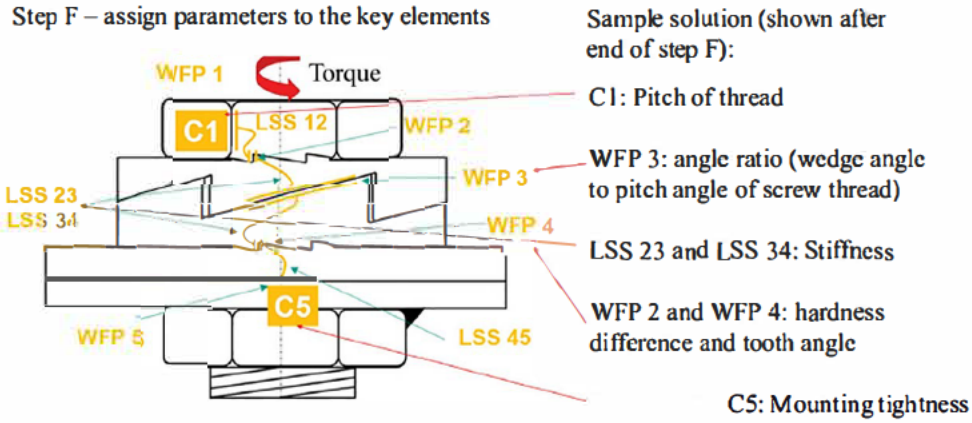


Figure 14. Assignment of parameters in the modelling training.

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 (e.g. described in Berger and Zhou (2014)) 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. This test is applied, as requirements for a parameterised approach like the *t* test are not met by the generated data and it is described as the nonparametric variant of the *t* test (compare e.g. McKnight and Najab (2010)). It is checked whether the randomisation 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 (compare e.g. Woolson (2008)), as it requires equivalent data quality to the Mann Whitney U test. 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 (compare e.g. Sprent (2011)) is used, as the variables are categorical and in some categories, too few data points are collected for using the Pearson Chi^2 test. The chosen significance level is $p = 0.05$.

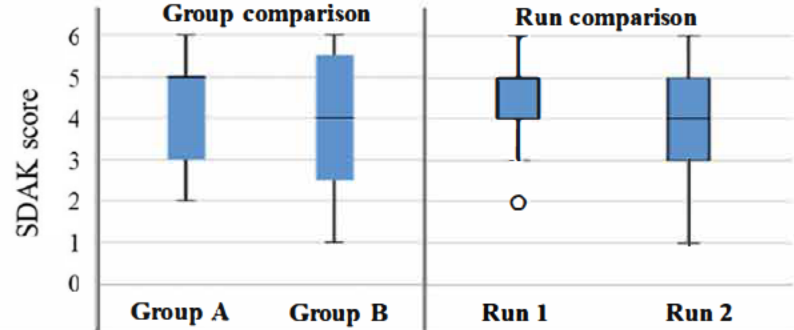
5. Results

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

5.1. *Impact of qualitative modelling on SDAK 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

Investigation of group and run influence through the Mann-Whitney U test



Mann-Whitney U	590	448
Z	0,266	1,322
p	0,791 > 0,05 ➔ r not assignable	0,186 > 0,05 ➔ r not assignable

Legend: Mann Whitney U = Value of the test statistic for this test
Z = Standardized random variable
p = Value of significance
r = Effect according to Cohen (1988)
SDAK = Specific design artefact knowledge

Figure 15. Analysis of the group and run's influence on the score in the system evaluation (change in systems understanding on system level).

were checked for outliers by analysing the box plot of the *SDAK 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.

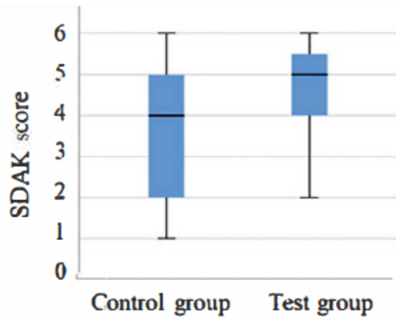
5.1.1. Initial data quality analysis

The most important initial data quality analysis is the evaluation, whether the modelling method has been used by the participants. 30 of the 36 participants delivered drawings of $C\&C^2$-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 4.3.4), it is assumed that they were concerned with the model building even though they might not have finished a model.

In Figure 15, an overview of the investigation of the group and run's influence on the change of system understanding of the 35 participants is given. The score in system evaluation represents the correctly rated evaluation by the participants and ranges from 0 to 6.

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 (23 students with

Impact of the modelling method on the SDAK



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

Legend:
- N = Number of participants in the test
- Mann-Whitney U = Value of the test statistic for this test
- Z = Standardized random variable
- p = Value of significance
- r = Effect according to Cohen (1988)
- SDAK = Specific design artefact knowledge

Figure 16. Analysis of the impact of the modelling method on the score in the system evaluation.

prior theoretical knowledge of the C&C² approach) with the second run (12 scientific assistants without prior theoretical knowledge of the C&C² approach) also shows no significant effect. The whiskers show the maximum and minimum values. The blue box resembles the area from lower to higher quartile and shows 25–75% of the data. It also contains the median (black line), which lies at the 75% limit of the box for group A (left side) and run 1 (right side). As no effect is shown from group comparison and run order, the data quality is assumed to be sufficient for further analysis.

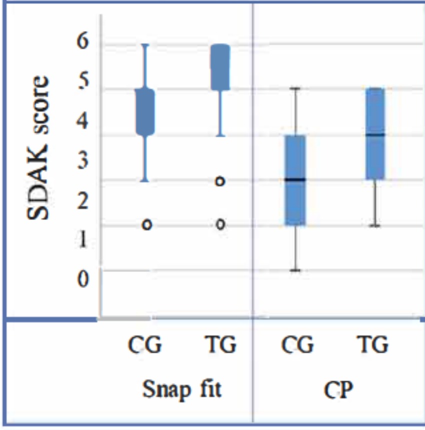
5.1.2. SDAK for detail design on the system level

For the investigation of SDAK at the *system level*, the correct assignment of behaviour to a given structure of a technical system is evaluated here. The results of the control group and the test group are compared in Figure 16.

On the left side of Figure 16, 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 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 17 shows an overview of the results differentiated into the two systems.

SDAK: 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: N = Number of participants in the test
Mann-Whitney U = Value of the test statistic for this test
Z = Standardized random variable
p = Value of significance
r = Effect according to Cohen (1988)
SDAK = Specific design artefact knowledge
CG = control group
TG = Test group
CP = Cartridge press

Figure 17. Analysis of a detailed consideration of each system on its score in the system evaluation (change in SDAK).

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 SDAK shows a significant difference with medium effect r. In summary, the increased gain of system understanding occurs in both systems, therefore, the hypothesis SH1 is deemed approved.

5.2. Impact of qualitative modelling on SDAK on 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 (see Figure 1) 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.

5.2.1. SDAK for detail design – function-relevant states

The results of the investigation of function-relevant states are shown in Table 2.

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

Table 2. Overview of the investigation of detail level regarding function-relevant system states related to hypothesis H2.1.

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			

NRS = Non-relevant states FRS = Function-relevant states.

Table 3. Overview of the investigation of detail level regarding function-critical areas related to hypoth-esis H2.2, the majorities of the participants are marked in bold (snap fit joint, mostly correct) and italic (cartridge press, mostly not correct).

Selected option		Arbitrary + RS	Only FP	FP and FC	Only FC	Statistical analysis		
		Inadequate	Missing	Correct, but				
Explanation		system understanding	critical elements	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			

RS = Residual structure FP = areas participating in the function FC = Function critical areas.

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-Chi^2 test is violated. Here, both systems show no statistically significant effect of the modelling method on system understanding ($p > 0.05$). Therefore, no evidence has been found to approve hypothesis H2.1.

5.2.2. SDAK for detail design – function critical areas

The distribution of the results for the investigation of critical areas is shown in Table 3.

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 car-tridge 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-Chi^2 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 hypothesis H2.2.

6. Discussion

Due to investigating the effects of a design method using a newly developed operationalisation, the discussion and corresponding limitations are presented for the results and the implications for the research methodology used separately. Section 6.1 discusses the observed effects of qualitative modelling on *SDAK* for detail design in a wider context, while Section 6.2 reflects on the chosen operationalisation of *SDAK* for detail design. Section 6.3 then considers limitations concerning the study design chosen.

6.1. Effects of qualitative modelling on specific design artifact knowledge

The research question is partially approved through the investigated hypotheses. The results regarding the hypothesis H1 show that the usage of the modelling method of the C&C^2-Approach significantly increases specific design artifact knowledge on the system level. The results regarding the hypotheses H2.1 and H2.2 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 investigated modelling method on specific design artifact knowledge in detail design. Up to now, it was known that the usage of already built up C&C^2-Models supports understanding of technical systems (Gladysz and Albers 2018). The usage of already built-up models, however, is only one of the applications of qualitative models in detail design. With this investigation, the positive impact of the modelling method itself on *SDAK* has been shown in comparison to intuitive approaches on the system level. This means that the modelling method of the C&C^2-Approach taught in the video-based training leads to increased understanding of the technical system even if the method users are no experts in this approach.

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 *SDAK* score. 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 scale, indicating that this system's difficulty is suitable for such a task. To gain more clearly detectable effects in future investigations on the system level, the system difficulty of the snap fit joint has to be increased or another, comparably difficult technical system needs to be prepared as stimulus. 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 analyse, 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.

6.2. Insights on the developed operationalisation for SDAK

A statistically significant effect of the applied qualitative modelling method on *SDAK* for detail design could be identified. This indicates, that the newly developed operationalisation is able to assess differences in *SDAK* on a *system_level* at sufficient granularity to enable a statistical analysis of results. By focusing on the knowledge generated rather than on the outcomes of the design method, the developed operationalisation might be used either to validate other design methods or to further explore the generation of *SDAK*.

The above discussed influences of the technical systems chosen as stimuli regarding complexity and ease of analysis still might influence the obtained results. Also, we cannot preclude that the operationalisation might assess aspects of knowledge other than *SDAK*. Further investigations using alternative design methods or alternative operationalisations for *SDAK* are necessary to generate additional evidence in this regard.

Assuming that SDAK was correctly assessed at the system level, there are several possibilities, why no effects could be detected at the detail level. Including a) SDAK is not generated as assumed, b) the operationalisation of SDAK at the detail level does not reflect the actual components of SDAK:

(a) Dividing SDAK into system and detail level had the background that a systematic generation of SDAK was assumed. In other words, it was assumed engineering designers had to understand which details of the structure and which system states influence system behaviour in relation to its function to correctly appoint system variants to expected behaviour. However, this reflects an academic point of view. It might be, that we now see a phenomenon that is often present with engineering designers in industry. They often design based on a gut-feeling, without being able to express the 'why' of their decisions. Based on their experience, brilliant ideas can be implemented in detail design. However, they can hardly explicate the reasons of their detail design decisions because they are based on tacit knowledge.
(b) If *SDAK* is generated systematically, the chosen components *function-relevant states* and *function critical areas* might still not reflect actual components of *SDAK*. Additionally, the chosen way to assess the detail knowledge might have been unnatural to the participants and difficult to perform as a quite artificial situation was created using depictions of states and clusters of system areas.

A possible strategy to mitigate the described shortcomings in future studies could be to include more realistic tasks which require application of the necessary knowledge. For example, participants could be asked to change the detail design of a given technical system so it is able to fulfil its function. By interpreting the changes made, conclusions can be drawn on detail understanding within *SDAK*.

6.3. *Limitations*

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 *SDAK* 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 studies, the modelling method used in this study can be used as a baseline to compare new or improved modelling methods in embodiment design.

7. Conclusion

The investigation presented here was able to determine a statistically significant effect of qualitative modelling on *SDAK* at the system level and thus identify a potential support for the generation of *SDAK* for detail design. The effects achieved by modelling with the exemplary chosen design method can also be potentially achieved by alternative modelling methods or other design methods. With the present study, we form a benchmark for further investigations.

Concerning the exploration of how *SDAK* for detail design is generated, no effects of the chosen modelling method could be identified. This might be attributed to the reasoning underlying the operationalisation on the detail level of *SDAK*, the operationalisation itself, the study design or the stimuli chosen. With the present scoping study, we have taken the first step to investigate the generation of *SDAK* for detail design. Further studies are needed to expand on the insights gained into the generation of *SDAK*. Even if no conclusive statement could be derived on how *SDAK* is built up in detail, a statistically robust research method could be developed and starting points for further research could be identified.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Patric Grauberger http://orcid.org/0000-0002-8367-3889
Matthias Eisenmann http://orcid.org/0000-0002-1007-4260
Sven Matthiesen http://orcid.org/0000-0001-5978-694X

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