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Teaching Concept of a Modeling Approach for the Analysis of Embodiment Function Relations for Product Engineering

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Abstract

The Extended Contact and Channel Approach (Extended C&C²-Approach) is a framework for analyzing and modelling of Embodiment Function Relations (EFR) in product engineering. Despite its potential, many students and professionals face challenges in understanding and applying its core principles and extensions. This paper presents and evaluates a modular training concept integrating short theory inputs, collaborative active-learning modules, and guided practice within the Live-Lab IP24/25 – Integrated Product Development. Results from a mixed-methods evaluation demonstrate that while foundational concepts are effectively taught, challenges remain in teaching advanced topics like the Designation Guideline and Functional Delimitation. This paper presents a validated instructional framework that connects the Extended C&C² modeling process to specific learning objectives and long-term behavioral outcomes. This framework supplements existing engineering education formats by explicitly focusing on EFR-oriented modeling proficiency. Limitations include a single-institution sample and limited statistical power, suggesting future multi-site comparative studies.

Keywords
Contact and Channel Approach, engineering education, modular training concept, embodiment function relations, technical analysis.

1. Introduction
The ability to systematically analyze Embodiment Function Relations (EFR) helps to support successful product engineering. These EFR connect geometric features of technical systems to their functional performance, aiding optimization, and innovation. The Contact and Channel Approach (C&C²-Approach) provides a framework for these tasks and enables users to document their findings. It emphasizes three key elements: Working Surface Pairs (WSP), Channel and Support Structures (CSS), and Connectors (C), enabling users to model interactions (Matthiesen, 2021). In response to practical challenges, the Extended C&C²-Approach introduces advanced tools, including a Designation Guideline for standardized terminology (Tröster, Schmidt & Albers, 2023) and the Functional Delimitation to distinguish between different functionalities within a single volumetric object (Tröster, Prager et al., 2023). However, engineering students and professionals often struggle to master the methodology due to its complexity and insufficient training opportunities (Tröster et al., 2025). As these benefits come with increased conceptual load, raising questions of how to teach the method effectively and how to support transfer from conceptual understanding to practical modeling behavior.

To bridge this gap, this study presents a modular training concept tailored for engineers, who may have never used the approach before. Conducted in the Live-Lab IP24/25, this concept employs active learning methods to improve comprehension and application of the Extended C&C²-Approach. This paper aims to evaluate the effectiveness of this concept through two research questions:

- How can we effectively and time-efficiently teach a complex modeling method, such as the Extended C&C²-Approach, with its multiple extensions?
- How does the training effect the participants' ability to apply the Extended C&C²-Approach?

2. State of the Art

This chapter provides a conceptual background for the Extended C&C-Approach in modeling Embodiment Function Relations (EFR). After outlining the original constructs and recent extensions, we provide a brief description on active and collaborative learning for methodological skills in engineering.

2.1 The Extended C&C²-Approach

The Extended C&C²-Approach is based on the C&C²-Approach, which enables users to analyze technical systems through modeling of EFR. Therefore, it uses Working Surface Pairs (WSP), that represent the points of interaction where energy exchange occurs (see Figure 1). Channel and Support Structures (CSS) lead and transfer energy, information, and matter. Connectors (C) ensure that influences outside of the design space are included in the modeling process. (Matthiesen, 2021)

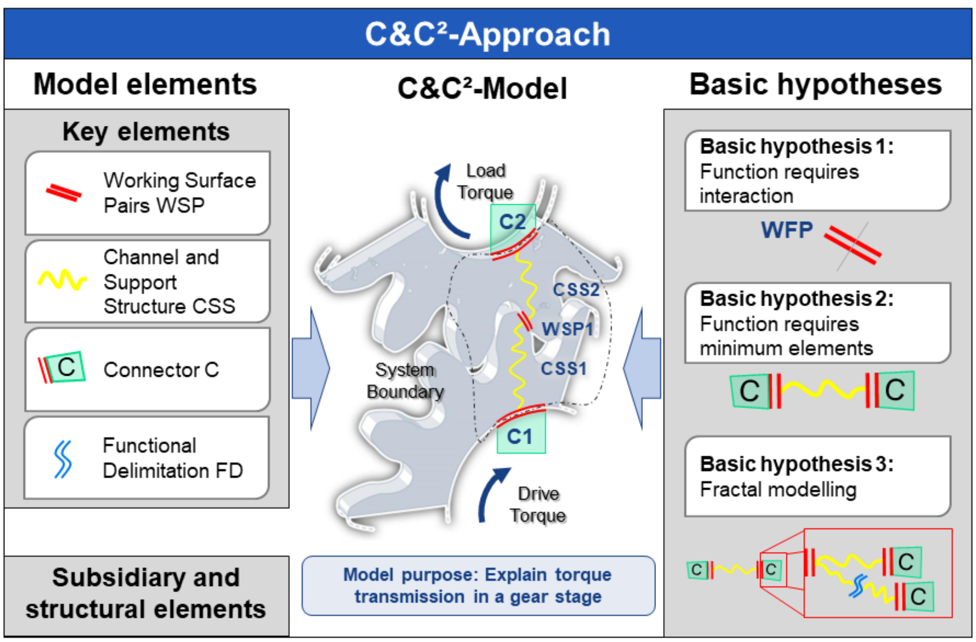

Figure 1. Adapted summary of the C&C²-Approach with adjustments like color code (Working Surface Pair = red; Channel and Support Structure = yellow; Connector = green; Functional Delimitation = blue) and example of Functional Delimitation, based on (Matthiesen, 2021)

To address emerging challenges in technical modeling, several extensions to the original C&C²-Approach were developed. First a Designation Guideline standardizes the terminology used to describe components, ensuring consistency and clarity across documentation. It also supports the link between the visual model and the textual documentation. (Tröster, Schmidt & Albers, 2023). The Functional Delimitation allows distinguishing multiple functions within a single CSS, enhancing the precision of the analysis (Tröster, Prager et al., 2023).

These enhancements contribute to more precise modeling and cross-disciplinary communication in engineering teams. However, they also increase methodological complexity and cognitive load, making the teaching and learning of the Extended C&C²-Approach a didactic challenge that requires carefully designed training formats.

2.2 Teaching and Learning Complex Modeling Methods in Engineering
Teaching complex modeling methods, such as the Extended C&C² Approach, requires educational strategies that go beyond traditional lecture-based instruction. Traditional lecture-based formats prioritize declarative knowledge and rules yet often fall short in supporting procedural transfer to authentic tasks. This is important for understanding and using methodological tools in product engineering.

Research in engineering education has shown that it is important to use active learning approaches, where learners develop understanding through solving problems and interacting with their peers (Freeman et al., 2014; Prince, 2004). Methods like the jigsaw classroom (Aronson, 1978; Hänze & Berger, 2007) and problem-based learning have been shown to get students working together, keep them interested, and help them remember what they learn.

In product engineering, these same ideas are used in Live-Lab environments (Albers, Walter et al., 2018). These environments combine theoretical instruction with real-world design and analysis tasks. These environments let students see how design choices, system behavior, and how well it works all interact with each other. This is like the way EFR modeling requires students to think analytically.

Despite these advancements, there is still a need for training ideas that have been proven to work, especially when it comes to system modeling. This is especially true for approaches like the C&C²-Approach that combine physical movement and abstract thinking.

2.3 Modular Training Concepts for Methodical Learning
Modular training programs are an effective way to teach complex technical methods in a way that is organized but can change. By breaking a method into small, connected parts, they help participants learn from the easiest to the hardest concepts at a pace that is right for them (Kolmos et al., 2016).

In engineering design education, modular approaches help integrate different learning objectives, such as theoretical understanding, methodological application, and reflective analysis. When combined with active learning techniques, modular concepts have been shown to improve knowledge retention, skill transfer, and motivation among engineering students (Froyd et al., 2012).

In the context of the Extended C&C²-Approach, modularization supports the gradual acquisition of modeling skills. These skills start with the identification of WSP and CSS, progress to the use of standardized notation (Designation Guideline), and conclude with advanced differentiation of functions (Functional Delimitation). This step-by-step process follows the Design Research Methodology (Blessing & Chakrabarti, 2009), which helps improve the training and the learners' skills over time.

3. Methodology
This chapter outlines the research design used to develop and evaluate the modular training for the Extended C&C²-Approach. Moreover, the chapter contains the evaluation methods as well as a description of the participants and the context of the study.
The study employs the Design Research Methodology (Blessing & Chakrabarti, 2009), which comprises four iterative phases:

1. **Clarifying Goals:** Identifying the objectives and success criteria for the training program.
2. **Descriptive Study I:** Assessing the initial knowledge and needs of the participants.
3. **Prescriptive Study:** Designing the training concept.
4. **Descriptive Study II:** Implementing and evaluating the training using Kirkpatrick's four-level evaluation model (Kirkpatrick & Kirkpatrick, 2006).

According to the model by Kirkpatrick and Kirkpatrick (2006), the training is evaluated based on the levels of reaction, learning, and behavior. Data was collected by using multiple questionnaires:

- **Münster Seminar Evaluation Questionnaire:** Evaluating participants' immediate reactions to the training with a standardized questionnaire (Thielsch & Hirschfeld, 2014)

- **Knowledge Tests:** Measuring learning outcomes one month after the training.
- **Panel Study:** Assessing long-term behavioral changes in the application of the C&C²-Approach compared to the pre-training state.

The training was conducted as part of the IP24/25 live lab, a practical course for mechanical engineering master's students at the Karlsruhe Institute of Technology (KIT) (Albers, Bursac et al., 2018; Albers, Walter et al., 2018). A total of sixteen students took part, from the fields of mechanical engineering (11), industrial engineering (3), mechatronics (1), and electrical engineering (1). The group was characterized by heterogeneous prior knowledge in the C&C²-Approach.

4. Results

This chapter reports empirical findings from implementing the training in a Live-Lab setting. We first describe the structure and delivery of the intervention, followed by learner reactions, delayed knowledge outcomes, and indicators of behavioral change. We then summarize perceived barriers to application to inform subsequent refinement.
The training is divided into two parts. The idea is to teach the Extended C&C²-Approach. This is how it is put into practice:

- **Part 1 Fundamentals (40min):** Introduces the core elements of the C&C²-Approach, including Working Surface Pairs, Channel and Support Structures, and Connectors.
- **Part 2 Extensions (70min):** The jigsaw classroom method consists of four modules aimed at teaching the extensions of the C&C²-Approach (see Figure 2), followed by a final practical exercise.

The Participants rated the training in the reaction questionnaire with an average score of 12.9 out of 15 points, indicating a positive reception. Most of the participants stated in comments they would recommend the training to others. Feedback from evaluation surveys highlighted, among other things, that the media and learning materials used were perceived by the students as helpful and of high quality.

Approximately one month after the training, the average test score was 11.9/20. Items targeting foundational constructs (identification of WSP, CSS, C; modeling of EFR) showed higher correctness than items that required applying the Designation Guideline or performing Functional Delimitation. The pattern suggests that learners retained core concepts but found advanced segmentation and standardized nomenclature more demanding. This is consistent with the anticipated progression from declarative understanding to procedural fluency.

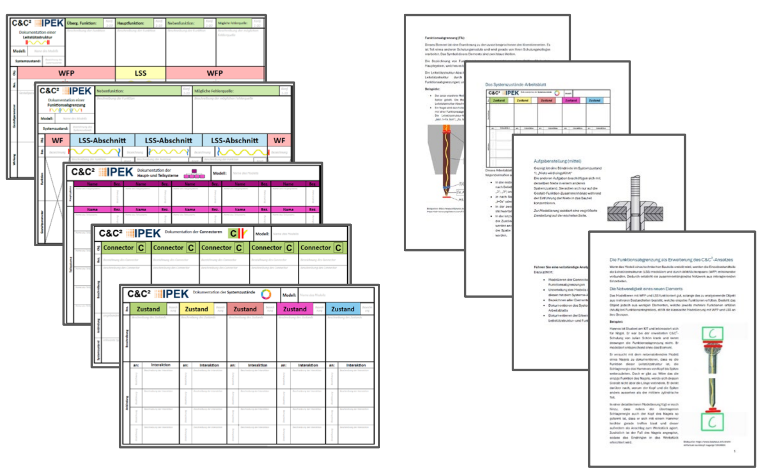

Figure 2. Examples of the created worksheets. There are worksheets to document results of the modelling of Embodiment Function Relations (EFR) in a structured way such as Working Surface Pairs, Functional Delimitation, the product architecture, Connectors, and system states (left side). Explanatory sheets intend to help to understand the approach by given examples (right side).

Panel responses indicated increases in the systematicity of analyses and in the frequency of documentation after training. Learners reported using EFR-based reasoning more deliberately and recording modeling decisions more consistently. While self-report cannot substitute for direct artifact analysis, the trend aligns with the training's emphasis on standardized documentation and collaborative consolidation of models (see Figure 3).

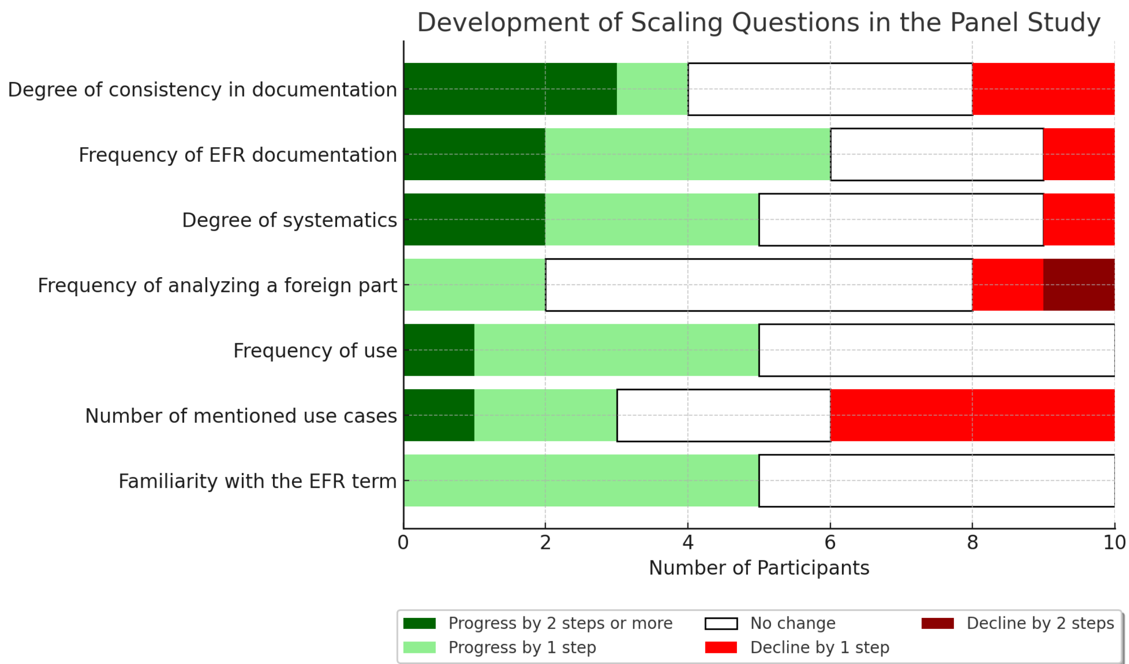

Figure 3. Development of scaling questions in the panel study

Participants noted several barriers to routine use: (i) the time effort associated with modeling and documentation, (ii) limited team acceptance or familiarity within project groups, (iii) uncertainty about application opportunities, and (iv) lack of confidence in correct application of advanced extensions. These barriers point to a need for organizational support and for resources that lower the activation energy for applying Extended C&C²-Approach outside the training setting.

5. Discussion

This chapter interprets the results with respect to the research questions. We discuss how the modular, active-learning design supports the acquisition and transfer of EFR competence, identify remaining challenges for advanced concepts, and derive implications for instructional practice. The text also explains the limitations and what more work could be done to improve the teaching in the future.

5.1 Answering Research Questions

The results provide insights into the effectiveness of the training concept and highlight areas for further improvement. Each research question is addressed in detail below:

RQ1: How can we effectively and time-efficiently teach a complex modeling method, such as the Extended C&C²-Approach, with its multiple extensions?

To teach the foundational elements of such a modeling method effectively, a structured training concept was developed using established didactic principles like the Jigsaw Classroom method. The training concept emphasizes active engagement, combining theoretical instruction with practical exercises. The design of the training concept allows participants to progressively deepen their knowledge, starting from basic concepts and advancing to complex applications, fostering comprehension and retention. The concept makes it possible to teach the foundation and a varying number of in-depth topics in a time-efficient manner.

RQ2: How does the training affect the participants' ability to apply the Extended C&C²-Approach?

The training demonstrated a positive impact on participants' ability to apply the Extended C&C²-Approach. Evaluations showed improvements in participants' systematic analysis and modeling of technical systems, as evidenced by their responses in post-training tests and practical applications. Although initial knowledge of the basic C&C² concepts varied, the training bridged some of these gaps, particularly by introducing enhancements such as Functional Delimitation and the Designation Guideline. Participants exhibited increased proficiency in modeling and documenting EFR, with some reporting the practical integration of these skills in their projects. However, further iterations of the training are recommended to address challenges such as varying prior knowledge and time constraints, ensuring broader applicability and deeper learning.

5.2 Implications for Engineering Education

Compared to other method trainings (e.g., TRIZ workshops, SysML modules), which typically focus on conceptual toolsets or notation skills in isolation, the present design introduces a more holistic workflow. By coupling embodiment-based reasoning with standardized documentation (Designation Guideline) and segment-wise functional differentiation (Functional Delimitation), it facilitates the transfer from conceptual understanding to documented analysis behavior under project-like constraints. This integration demonstrates that a modular training concept can effectively introduce complex technical methodologies such as the Extended C&C²-Approach.

To fully realize this potential, several measures are recommended:

1. **Time requirement:** Allocate more time to the modules to allow more in-depth engagement with the topic.
2. **Promote Team Integration:** Conduct team-wide workshops and provide leadership with evidence-based examples of the approach's benefits to encourage wider adoption.
3. **Strengthen Long-Term Support:** Provide post-training resources, such as video tutorials or online forums, to address participant questions and support ongoing skill development.
4. **Leverage Digital Tools:** Develop software or online platforms to support modeling tasks, reducing the time required for manual application and simplifying complex analyses.

5.3 Limitations

This study is subject to several limitations. The number of participants was small (n=16) and limited to one university course, which constrains the generalizability of the findings. In addition, the heterogeneity of prior knowledge in the C&C²-Approach complicates the interpretation of individual learning gains. The evaluation was restricted to a single semester, leaving long-term effects on the ability to apply the Extended C&C²-Approach in academic or industrial contexts unexplored.

6 Summary and Outlook

This study designed and evaluated a modular, active-learning training for the Extended C&C² Approach to teach Embodiment Function Relations (EFR) in product engineering. In a Live-Lab setting with master's students, participants reported positive reactions, demonstrated retained knowledge after a delay, and indicated increased systematic analysis and documentation behavior. Advanced elements, especially Functional Delimitation and standardized nomenclature per the Designation Guideline, remained comparatively demanding.

In relation to the research questions, the results suggest that (RQ1) a compact, modular sequence with peer explanation and guided practice is effective and time-efficient for introducing complex modeling methods, and (RQ2) the training supports early application, though additional scaffolding is advisable for advanced segments. The contribution of this work is a validated instructional structure that links Extended C&C² content to staged learning objectives and artifacts, enabling systematic teaching of EFR-oriented modeling within typical course constraints.

Looking forward, this paper identifies several areas for further refinement and exploration:

- **Customization for Diverse Audiences:** Tailoring content to varying levels of expertise will make the approach more efficient.
- **Long-Term Evaluation:** Future studies should evaluate the training concept in a long-term manner to assess the outcomes according to Kirkpatrick and Kirkpatrick's model.
- **Integration of Digital Tools:** Interactive software can simplify complex analyses and reduce the time burden for participants.
- **Organizational Adoption:** Workshops and case studies demonstrating the approach's value could foster team-wide acceptance.
- **Interdisciplinary Expansion:** Exploring applications in diverse fields can unlock new potential for the Extended C&C²-Approach.

By addressing these opportunities, the training concept can evolve into a versatile and impactful framework, advancing engineering education and professional practice. This progression will not only improve individual competencies but also enhance the ability of teams and organizations to tackle complex technical challenges effectively.

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Declaration of generative AI and AI-assisted technologies in the writing process

Generative AI tools (ChatGPT, DeepL, Grammarly, LanguageTool) were used for linguistic purposes, such as grammar correction and style improvement. All methodological decisions, data analysis, results, and interpretations originate from the authors without AI involvement.

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