Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 136 (2025) 576–581

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Evaluating the Extended C&C²-Approach in a Live Lab and in Practice

Peter M. Tröster[a]*, Tobias Dieck[a], Albert Albers[a]

[a]Karlsruhe Institute for Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

* Corresponding author. Tel.: +49-721-608-47252; fax: +49-721-608-46051. *E-mail address:* peter.troester@kit.edu

Abstract

Implicit knowledge of Embodiment Function Relations (EFR) is lost as experienced engineers retire. This initial study evaluates how the Extended C&C²-Approach, featuring structured templates and a Process Model, supports systematic modeling and documentation of EFR. Conducted with 27 students in a controlled Live Lab and nine engineers in industry, findings show the Extended C&C²-Approach enhances EFR identification and analysis. Future research will involve broader expert groups and digital integration to streamline documentation and facilitate knowledge transfer. By providing both methodology and practical tools, the Extended C&C²-Approach aims to mitigate knowledge loss in product development processes.

Keywords: C&C²-Approach; Design methodology, tools and technologies

1. Motivation

The departure of experienced engineers from the workforce due to demographic changes is resulting in a significant loss of implicit, product-specific knowledge [1]. This loss has severe implications for the innovative strength of companies, as much of this knowledge is not adequately documented. In particular, Embodiment Function Relations (EFR), which are essential for product development, are often implicit and thus at risk of disappearing [2]. To address this challenge, a Process Model based on the Contact & Channel (C&C²) Approach has been developed, designed to capture, document, and utilize EFR systematically to ensure knowledge continuity and support future product generations.

The systematic modeling and documentation of EFR are crucial for maintaining the innovative capacity of engineering teams [2]. The C&C²-Approach facilitates understanding of the physical interactions within a product, thereby ensuring that critical knowledge is transferred to newer generations of engineers. As the complexity of products continues to increase, the need for a structured approach to capture these intricate relationships becomes more pronounced [4]. The Extended C&C²-Approach aims to fill this gap by providing a formalized method for documenting and analyzing EFR, which are fundamental to product functionality and reliability.

2. State of the art

2.1. Contact & Channel Approach (C&C²-Approach)

The classical C&C²-Approach has been successfully used for decades to describe complex EFR graphically [5]. The model's key elements include Working Surface Pairs (WSP), Channel and Support Structures (CSS), and Connectors (C) (see Fig. 1) [6]. These elements provide a framework for visualizing and understanding the interactions between different components of a system. The C&C²-Approach is particularly effective in capturing the nuances of how physical components interact to achieve specific functions, which is critical in the design and optimization of complex systems.

2.2. Extended C&C²-Approach

The Extended C&C²-Approach adds further formalization and extends these concepts through tools such as the Designation Guide [7], Functional Delimitation [8], and a detailed

2212-8271 © 2025 The Authors. Published by Elsevier B.V.

10.1016/j.procir.2025.08.099

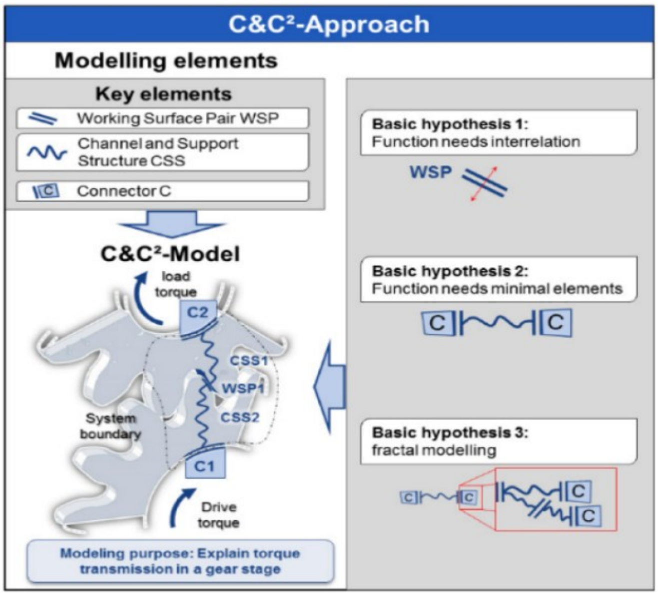

Fig. 1: Key model elements of the C&C2-Approach [3]

Process Model for analyzing EFR [9]. These extensions are intended to enhance the clarity, consistency, and applicability of the C&C²-Approach across different stages of product development.

2.2.1. Designation Guide

The Designation Guide provides a standardized approach for naming elements to enhance consistency and understanding across different systems. The guide ensures that all components are labeled in a uniform manner, which facilitates communication among team members and improves the overall quality of the documentation. The Designation Guide includes specific rules for naming Working Surface Pairs (slashes "//") and Channel and Support Structures (tilde "~"), making it easier to identify and reference these elements during the analysis and design phases. [7]

2.2.2. Functional Delimitation

Functional Delimitation (see Fig. 2) helps in segmenting complex single-piece systems, allowing more accurate reflection of different functions served by various sections. Functional Delimitation is particularly useful in systems where a single component performs multiple roles, such as in compliant mechanisms or multifunctional parts. By breaking down these components into distinct functional sections, engineers can better understand the contributions of each part to the overall system performance. [8]

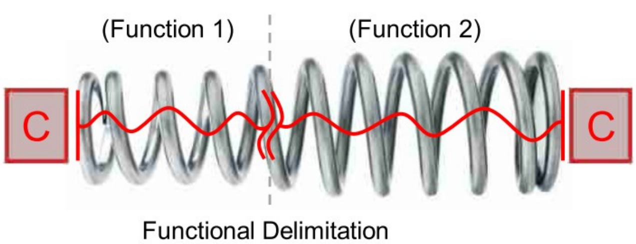

Fig. 2: Functional delimitation in a screw spring, translated from [8]

2.3. Process Model

The Process Model for analysis is a structured framework divided into five main sections, enabling a comprehensive and detailed analysis of EFR. Its purpose is to enable an in-depth analysis and documentation of knowledge to EFR, to preserve and to pass this knowledge to new engineers. [9]

There are five major steps in the Process Model. Each major step contains multiple mandatory as well as optional steps:

- **Pre-analysis:** This stage focuses on expanding knowledge and establishing system boundaries, setting a foundation for the analysis. Key tasks include identifying and documenting system components.
- **Analysis Phase:** Working Surfaces Pairs and Channel and Support Structures are identified and assigned to relevant functions. A confidence level is applied to assess the plausibility of identified EFR.
- **Documentation:** All identified EFR are systematically documented with the Designations Guide to make them accessible for further synthesis.
- **Synthesis:** The documented analysis information is utilized through variations of the EFR, targeting potential optimizations.
- **Evaluation and Adjustment:** The analysis concludes with an evaluation of model assumptions, making necessary adjustments to ensure the achievement of defined functions.

3. Research gap, research questions

Although the classical C&C²-Approach has been applied across various projects, the effectiveness of the new Process Model remains unevaluated. There is a need to understand whether the Extended C&C²-Approach provides significant improvements in the ability to analyze and document EFR compared to traditional methods. This study aims to fill that gap by examining how the Extended C&C²-Approach influences analysis skills in both educational and industrial settings.

3.1. Research questions

The following research questions were posed to close the research gap:

- To what extent does the developed Process Model improve the ability to systematically analyze complex Embodiment Function Relations?
- What difference can be observed in the number and quality of the Embodiment Function Relations found between students who use the Process Model and those who do not?
- How do users rate the Process Model in terms of its user-friendliness and usefulness?
- What obstacles and challenges arise when using the Process Model in practice?
- Is there a statistically significant difference in the number of identified optimization potentials between the application of the Process Model and conventional methods?

These research questions are aimed at evaluating both the quantitative and qualitative impacts of the Extended C&C²-

Approach. By addressing these questions, the study seeks to provide insights into the practical benefits and limitations of the Approach, as well as its potential for broader adoption in engineering practice.

4. Methodology

The study was conducted with 27 students from the Karlsruhe Institute of Technology (KIT) and 9 engineers from an automotive supplier.

The students participated in the Live Lab IP – Integrated Product Development. The Live-Lab IP is a realistic development environment in which up to 42 students work 5 months on practical tasks in cooperation with a company partner. This environment provides controlled conditions and enables methods and processes of product development to be researched in a development process that is as real as possible and at the same time allows the boundary conditions to be designed to a high degree. [10]

The students are studying for a master's degree in mechanical engineering and industrial engineering. The study was conducted over two days due to difficult scheduling conditions. On the first day, the groups were roughly the same size; on the second day, only one group was supervised. As the main aim was to gain insights into the Process Model and only one helper was present on the second day, there was only one group B on the second day.

The students were divided into two groups: Group A used the traditional C&C²-Approach, while Group B used the Extended C&C²-Approach with templates and guides. The analysis took place over two days, and participants received a 3D model of pliers to perform their analysis.

Group A was provided with basic documentation tools (see Fig. 3), while Group B received additional support in the form of templates based on the Extended C&C²-Approach. These templates included tools such as the System-State Function Diagram, a pre-analysis template for identifying system boundaries, and structured documentation forms for capturing EFR. The goal was to determine whether these additional tools could enhance the participants' ability to analyze and document EFR effectively.

Fig. 3: Distributed work package including a 3D print of the pliers

Nine engineers from the partner company were similarly divided into two groups. Group AF used the traditional Approach, while Group BF used the extended templates. The company study focused on a more practical application, using real-world components from the automotive industry. Data collection included quantitative evaluation of identified functions, intermediate states, and optimization suggestions, alongside a post-analysis survey to gather qualitative feedback on the usability and effectiveness of the Approach.

4.1. Study Design

The study design was based on a controlled comparison between the traditional and extended approaches. Participants were randomly assigned to either Group A or Group B to minimize biases related to prior knowledge or experience. Each group was given 90 minutes to complete their analysis, during which a supervising researcher was available to answer questions and provide clarification as needed. The supervising researcher also took notes on participants' behavior, including any difficulties encountered or questions raised during the analysis.

To ensure comparability, both groups were provided with a segmented 3D model of a pair of pliers, with each part pre-labeled. Group B also received training on how to use the extended templates, including specific instructions on Functional Delimitation and the use of the Designation Guide. The training session lasted 20 minutes and covered the key elements of the Extended C&C²-Approach, with a focus on how to apply these tools in a systematic manner.

4.2. Data Collection and Analysis

Data collection involved both quantitative and qualitative methods. Quantitative data included the number of functions, system states, and optimization suggestions identified by each group (see Fig. 4). These metrics were used to assess the effectiveness of the Extended C&C²-Approach in enhancing the participants' ability to analyze EFR. Qualitative data were collected through a post-analysis survey, which included Likert-scale questions and open-ended questions to gather participants' feedback on the usability and perceived value of the tools provided.

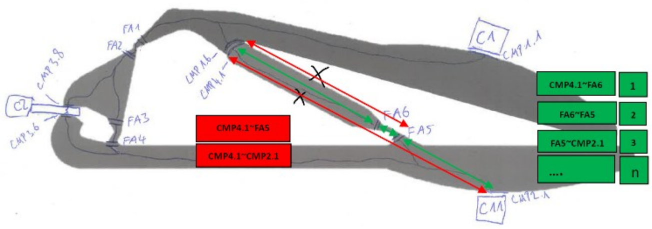

Fig. 4: Example of the correct counting of the shape sections based on an analysis result of a group from the study (red= incorrect, green= correct)

The quantitative data were analyzed using statistical methods to determine whether there were significant differences between the groups. The primary metrics of interest were the number of identified functions, the quality of the documented relationships, and the number of optimization suggestions. The qualitative data were analyzed thematically to identify common themes and insights related to the usability and effectiveness of the Extended C&C²-Approach.

5. Results

5.1. Quantitative Findings

The results of the quantitative analysis showed that Group B significantly outperformed Group A in several key areas (see Fig. 5). On average, Group B identified eight distinct functions, compared to Group A's five. Group B also identified more system states, including both primary states (e.g., "pliers open" and "pliers closed") and intermediate states (e.g., "opening" and "closing"). These intermediate states are critical for understanding the dynamic behavior of compliant mechanisms, which was a key focus of the study.

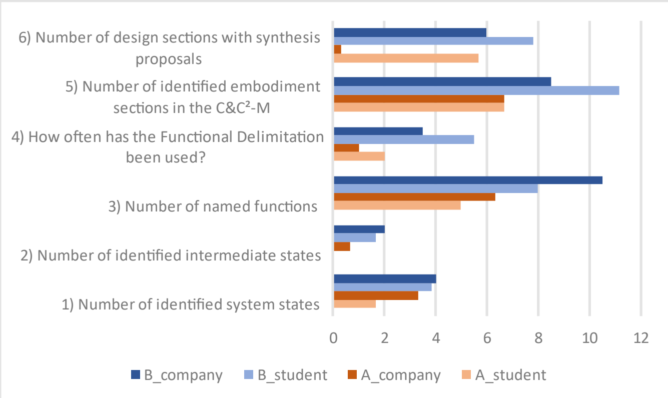

Fig. 5: Results comparing analysis results from A (without extended CCA) and B (with extended CCA) groups, students, and company employees

The use of Functional Delimitation allowed Group B to break down the system into more detailed segments, resulting in a more comprehensive analysis. Group B identified an average of four additional segments compared to Group A, which contributed to a more detailed understanding of the system's behavior. The Extended C&C²-Approach also led to a higher number of optimization suggestions, with Group B proposing an average of 25% more suggestions than Group A. These suggestions included specific modifications to improve ergonomics, enhance functionality, and reduce material usage.

5.2. Survey Results

The post-analysis survey provided additional insights into the participants' experiences with the Extended C&C²-Approach (see Fig. 6). Group B participants reported a higher level of satisfaction with the tools provided, with 75% indicating that the templates made the analysis process easier and more structured. In contrast, 87% of Group A participants felt that the existing tools were insufficient for conducting a detailed analysis of the compliant mechanism. Participants from Group B also highlighted the value of the pre-analysis template in helping them establish system boundaries and identify key components before diving into the detailed analysis.

Group BF (company engineers using the Extended C&C²-Approach) similarly indicated that the templates enhanced their understanding of the system and improved the accuracy of their analysis. However, both student and company participants in Group B reported that the training session was too brief, with 70% indicating that they would have benefited from more time to become familiar with the tools. This feedback suggests that while the Extended C&C²-Approach is effective, its implementation requires sufficient training to maximize its benefits.

6. Discussion

The study results support the efficacy of the Extended C&C²-Approach in enhancing the ability to analyze and document EFR. The use of templates and structured documentation aids provided a clear advantage over the traditional Approach, as evidenced by the higher number of identified functions, system states, and optimization suggestions. The Extended C&C²-Approach also facilitated a more detailed segmentation of the system, which is crucial for understanding the complex interactions within compliant mechanisms.

One of the key advantages of the Extended C&C²-Approach is its ability to standardize the analysis process, making it easier for engineers to communicate their findings and build on each other's work. The Designation Guide, for example, ensures that all components are labeled consistently, reducing the risk of miscommunication, and improving the overall quality of the documentation. The use of Functional Delimitation also allows for a more granular analysis, which can lead to more targeted and effective optimization suggestions.

However, the study also identified several challenges associated with the adoption of the Extended C&C²-Approach. The most significant challenge was the need for additional training. Participants in Group B reported that the 20-minute training session was insufficient to fully understand how to use the templates effectively. This suggests that more comprehensive training is necessary to ensure that users can take full advantage of the Extended C&C²-Approach. Additionally, the time allocated for the analysis was viewed as insufficient by some participants, particularly those in Group B who had to familiarize themselves with new tools during the analysis.

The findings also highlight the importance of pre-analysis in establishing a solid foundation for the analysis process. Group B participants who used the pre-analysis template were better able to identify system boundaries and key components, which facilitated a more focused and effective analysis. This underscores the value of providing engineers with structured tools that guide them through the initial stages of the analysis, helping them to establish a clear understanding of the system before delving into the details.

6.1. Practical Implications

The practical implications of this study are significant for both engineering education and industrial practice. For engineering students, the Extended C&C²-Approach provides a process model that helps them develop the skills needed to analyze complex systems systematically. By using the templates and guides provided, students can gain a deeper understanding of how different components interact and contribute to the overall functionality of a product. This is particularly important in the context of compliant mechanisms, where the interactions between components are often complex and difficult to capture using traditional methods.

In an industrial setting, the Extended C&C²-Approach has the potential to improve the efficiency and effectiveness of

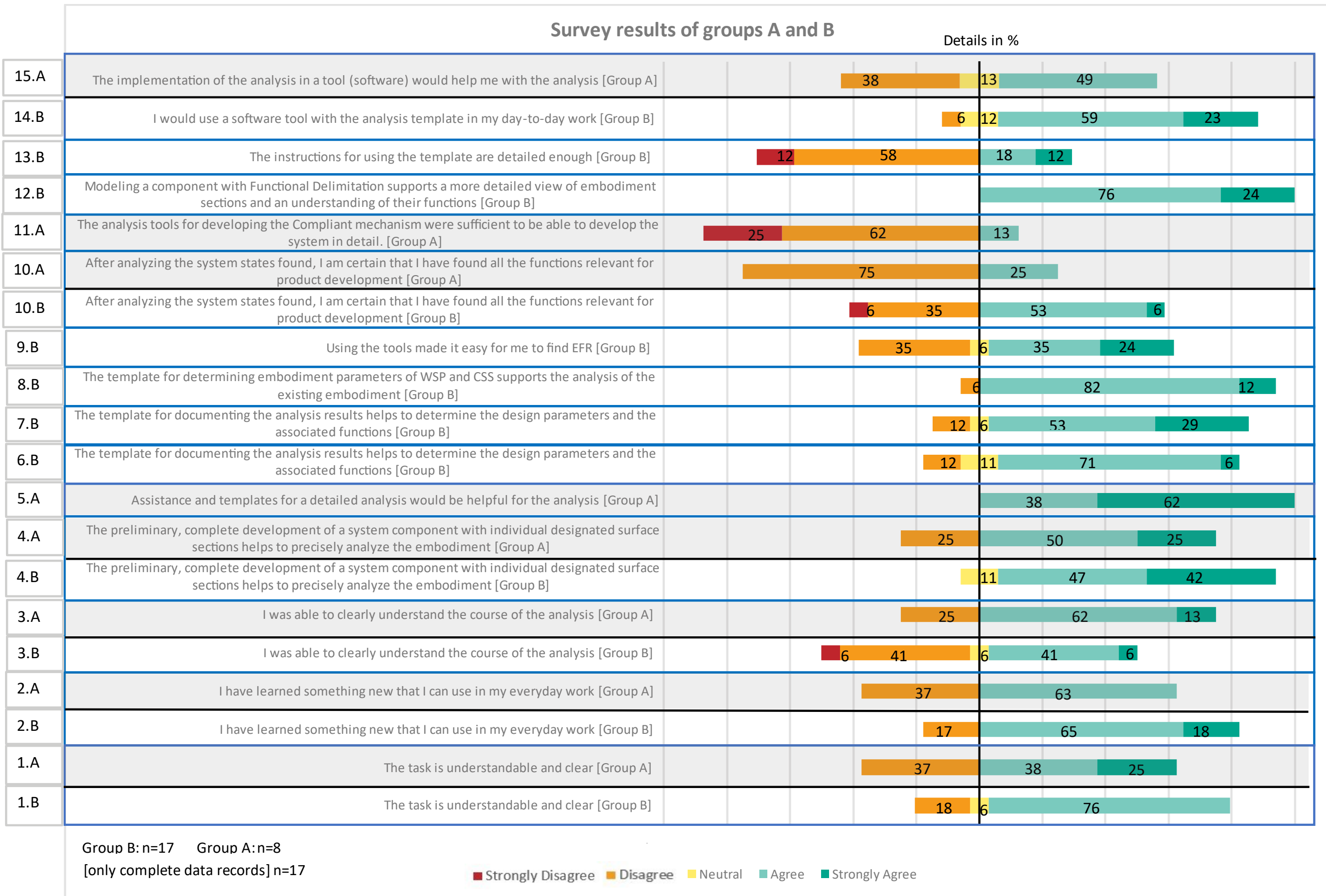

Fig. 6: Results of the online survey from the students

product development processes. By providing engineers with standardized tools for analyzing and documenting EFR, companies can ensure that critical knowledge is captured and retained, even as experienced engineers retire. This can help to mitigate the loss of tacit knowledge and support the development of innovative products that build on past successes. The use of Functional Delimitation can help engineers identify opportunities for optimization that may not be apparent when using more traditional Approaches.

6.2. Limitations and Future Work

While the results of this study are promising, there are several limitations that should be addressed in future research. One limitation is the relatively small sample size, particularly in the company study, which involved only nine engineers. A larger sample size would provide more robust data and allow for a more comprehensive evaluation of the Extended C&C²-Approach's effectiveness. Additionally, the study was conducted over a short period, with participants given limited time to complete their analysis. Future studies should consider extending the analysis period to allow participants more time to become familiar with the tools and conduct a thorough analysis.

Another limitation is the reliance on self-reported data from the post-analysis survey. While the survey provided valuable insights into participants' experiences, self-reported data can be subject to biases, such as social desirability bias or recall bias. Future research should consider incorporating more objective measures of usability and effectiveness, such as direct observations of participants' interactions with the tools or performance metrics related to the quality of the analysis.

Future work should also explore the integration of digital tools to support the Extended C&C²-Approach. Many participants indicated that digital versions of the templates would be helpful, particularly in terms of improving the efficiency of documentation and analysis. Developing software tools that incorporate the Extended C&C²-Approach could make it more accessible and user-friendly, particularly for engineers working in fast-paced industrial environments. Additionally, future research should investigate the applicability of the Extended C&C²-Approach to more complex systems, such as those involving multiple components or dynamic interactions, to further validate its effectiveness.

7. Conclusion and Outlook

The Extended C&C²-Approach demonstrated promising results for systematically analyzing and documenting Embodiment Function Relations (EFR). By providing structured templates and documentation aids, engineers and students were able to identify more functions, system states, and optimization opportunities compared to the traditional approach. However, the results also highlight key challenges, such as the necessity of additional training and the relatively small number of participants, particularly in the industrial context.

Future research should address these limitations by expanding the study to include a larger and more diverse pool of experts from multiple industries. This broader involvement is expected to strengthen the statistical significance of our findings and enable a more comprehensive evaluation of the Extended C&C²-Approach's effectiveness. Furthermore, we plan to develop digital tools, reducing the time needed for training and improving documentation consistency. A software tool, which is currently in development, is intended to significantly streamline the application of our templates in real-world product development processes.

Additionally, longitudinal studies will be conducted to investigate how well the Extended C&C²-Approach facilitates the retention and transfer of EFR-related knowledge over extended periods, particularly in environments with high employee turnover. By continually refining both the methodological framework and the supporting tools, we aim to establish the Extended C&C²-Approach as a standard practice for systematically capturing and leveraging engineering knowledge in diverse industrial settings

In conclusion, the Extended C&C²-Approach represents a valuable advancement in the field of engineering design methodology. By providing a process model for analyzing and documenting EFR, it has the potential to enhance both the educational experience of engineering students and the efficiency of product development processes in industry. With further refinement and validation, the Extended C&C²-Approach could become a standard tool for capturing and utilizing critical engineering knowledge, helping to ensure the continuity of innovation in the face of demographic challenges.

Acknowledgement

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 509078026.

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

During the preparation of this work the authors used ChatGPT, DeepL, Grammarly, and LanguageTool in order to improve readability, grammar and to support translation into well written English. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

[1] Adenauer, S., 2015. Demografischer Wandel und Auswirkungen auf Unternehmen, in *Leistungsfähigkeit im Betrieb: Kompendium für den Betriebspraktiker zur Bewältigung des demografischen Wandels*, Springer-Vieweg, Berlin, Heidelberg.

[2] Matthiesen, S., Grauberger, P., 2024. *Konstruktionswissen für Ingenieure*. Springer Berlin Heidelberg, Berlin, Heidelberg.

[3] Matthiesen, S., Grauberger, P., Sturm, C., Steck, M., 2018. From Reality to Simulation – Using the C&C²-Approach to Support the Modelling of a Dynamic System, in *28th CIRP Design Conference 2018*, Nantes, Frankreich, p. 475.

[4] International Council on Systems Engineering (INCOSE), Editor, 2021. *Systems Engineering Vision 2035: Engineering solutions for a better world*.

[5] Grauberger, P., Wessels, H., Gladysz, B., Bursac, N. *et al.*, 2020. The contact and channel approach – 20 years of application experience in product engineering *31*, p. 241.

[6] Matthiesen, S., 2021. Gestaltung - Prozess und Methoden, in *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung*, Springer Berlin Heidelberg, Berlin, Heidelberg, p. 397.

[7] Tröster, P.M., Schmidt, D., Albers, A., 2023. A Designation Guide for Consistent Cross-System-Level Modeling of Embodiment Function Relations *119*, p. 1222.

[8] Tröster, P.M., Prager, F., Schmid, D., Albers, A., 2023. Modellierung von abschnittsweisen Gestalt-Funktion-Zusammenhängen mithilfe des C&C2-Ansatzes: Modeling of Embodiment Function Relations using the C&C2-Approach, in *Stuttgarter Symposium für Produktentwicklung SSP 2023 | Tagungsband | Stuttgart, 25. Mai 2023*, p. 175.

[9] Tröster, P.M., Dieck, T., Albers, A., 2025. Development of a Process Model for the Extended C&C²-Approach for Analyzing and Synthesis of Embodiment Function Relations (submitted) *2025*.

[10] Walter, B., Albers, A., Haupt, F., Bursac, N., 2016. Produktentwicklung im virtuellen Ideenlabor – Konzipierung und Implementierung eines Live-Lab, p. 283.