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Development of a Process Model for the Extended C&C²-Approach for Analyzing and Synthesis of Embodiment Function Relations

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Abstract

We introduce the Extended C&C²-Approach for systematically capturing Embodiment Function Relations (EFR) to address knowledge loss from departing engineers. The classical approach lacks sufficient detail for novices. We propose a five-step Process Model, incorporating the Designation Guide, Functional Delimitation, and structured templates. Validated in a Live Lab and an industrial context, this method improves EFR documentation, knowledge retention, and clarity. Our findings indicate that codifying EFR fosters innovation and efficient product development. Future work will extend digital tool integration and explore broader industry contexts to further streamline EFR capture and analysis.

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

1. Introduction

Demographic shifts in recent years have accelerated the retirement of experienced engineers, resulting in the loss of critical product-specific knowledge. This challenge is especially pronounced for Embodiment Function Relations (EFR), which capture how a product's physical embodiment underpins its functionality. While these EFR insights often reside tacitly in the minds of experienced personnel, their departure leaves organizations vulnerable to knowledge gaps that can undermine innovation.

Although the classical Contact and Channel (C&C²) Approach provides a valuable conceptual framework for modeling EFR, it does not offer sufficient procedural detail to systematically document EFR, particularly for engineers with limited experience. To address this shortcoming, the Extended C&C²-Approach was developed. It is intended to improve documentation through new elements like the Functional Delimitation and a Designation Guide. Furthermore, it introduces a structured five-step Process Model aimed at guiding engineers step by step in analyzing, recording, and leveraging EFR. By codifying previously implicit knowledge, the Extended C&C²-Approach preserves critical expertise and facilitates its transfer to newer generations of engineers.

This paper presents the newly developed Process Model for the Extended C&C²-Approach, highlighting how it improves clarity, consistency, and practical applicability.

2. State of the Art

2.1. Classical C&C²-Approach

The classical C&C²-Approach has been used successfully for decades to model Embodiment Function Relations (EFR) graphically [1]. This approach aims to support thinking processes during product development, focusing on analysis and visualizing EFR. The model's key elements include Working Surface Pairs (WSP), Channel and Support Structures (CSS), and Connectors (C). These elements form the core structure

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of a C&C² model and provide a framework to better understand the physical interactions and the implications of these interactions on a products functionality. [2]

The classical C&C²-Approach has proven effective in capturing the nuances of physical component interactions, which is crucial for the design and optimization of systems. However, as the complexity of products and their requirements grows, additional formalization is needed to ensure that EFR can be captured consistently across different applications and project phases, as well as for later use to teach artificial intelligence about EFR.

2.2. Extended C&C²-Approach

The Extended C&C²-Approach introduces several enhancements to address the limitations of the classical C&C²-Approach. It bridges the lack of a standardized designation and unclear modelling of EFR in single parts through tools such as the **Designation Guide** [3], **Functional Delimitation** [4], and a more detailed five-step **Process Model** for analyzing EFR. These extensions are intended to enhance the consistency, clarity, and applicability of the C&C²-Approach across various stages of product development.

Designation Guide: The Designation Guide provides a standardized approach for naming elements, which enhances consistency and understanding across different systems. It ensures that all components are labeled in a uniform manner, thereby facilitating communication among team members and improving the quality of documentation. [3]

Functional Delimitation: This tool helps to segment complex systems into distinct functional sections, allowing for a clearer understanding of the roles played by different parts of a system. Functional Delimitation is particularly useful in systems where individual components perform multiple functions. [4]

These enhancements aim to make the classical C&C²-Approach more robust and applicable to a wider variety of product development projects by providing additional tools and guidelines for modeling and analyzing EFR.

The classical C&C²-Approach has primarily been used for problem analysis and solution generation. As stated in the introduction, we now focus on documenting knowledge. Therefore, an existing Process Model must be adapted and extended to effectively capture and retain EFR in a consistent manner across different projects and phases.

Therefore, it is necessary to develop a new Process Model that guides engineers through each step of the analysis and synthesis of EFR, ensuring consistency, completeness, and the effective documentation of design knowledge.

3. Research Questions and Research Approach

The focus of this paper is on developing a Process Model for the Extended C&C²-Approach that facilitates the systematic analysis, synthesis, and documentation of Embodiment Function Relations (EFR). The research questions are as follows:

- **RQ1:** What can be key elements and steps for a proposed Process Model to make use of the Extended C&C²-Approach?
- **RQ2:** What challenges arise during the implementation of the proposed Process Model, and how can they be addressed?

4. Methodology

The methodology for developing the Process Model is based on the Design Research Methodology (DRM) [5], which provided a structured, iterative approach to ensure that the model effectively addressed the challenges faced in systematically capturing Embodiment Function Relations (EFR).

4.1. Development of the proposed Process Model

In the Descriptive Study I, a detailed literature review and empirical investigations were conducted to understand the limitations of the classical C&C²-Approach. These investigations helped establish the requirements for the new Process Model. A Reference Model was created to visualize the relationships between the various requirements and the expected outcomes of the new Process Model. This Reference Model formed the basis for an Impact Model, which identified key factors that would support the successful implementation of the Process Model. The Impact Model specifically focused on the tools and workflows necessary to improve the analysis and documentation of EFR.

4.2. Application and Evaluation

To validate the proposed Process Model, an initial study was conducted in a Live Lab setting with students from the Karlsruhe Institute of Technology (KIT), and with practicing engineers in an industrial context. [6]

5. Results

5.1. Proposed Process Model

The answer to the research question **RQ1**, on what key elements and steps should be considered, is given in this section.

There are five steps for the proposed Process Model for the Extended C&C²-Approach. All steps and key elements of the proposed Process Model for the Extended C&C²-Approach are described in the following. We present the objective for each step before describing the steps underlying it:

5.1.1. Step 1: Pre-Analysis (see Fig. 1)

Objective: Establish a strong foundation for the analysis by gathering necessary information, defining the scope, and setting clear objectives.

Follow these Steps:

1. **Gather Existing Information:** Collect all available data and knowledge about the system under investigation, including technical specifications, past analyses, expert in-

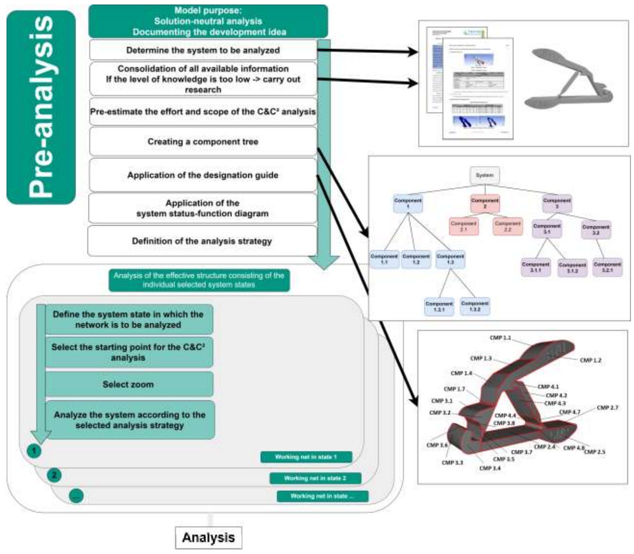

Fig. 1: Step 1: Process of the Pre-Analysis with an example. The example shows gathering of existing information of a compliant mechanism plier, a hierarchical structure of components and help for the designation of the surfaces

put, use-cases, and relevant literature to create a comprehensive knowledge base for informed analysis. It is possible to use existing approaches in order to gain those information (e.g. FMEA, persona method, etc.).

2. **Define Scope and Purpose:** Set the boundaries of the analysis and clarify the goals, specifying which aspects of the system will be the focus to ensure the analysis remains targeted and relevant to the development objectives.
3. **Create a Component Tree and Naming Convention:** Develop a component tree to visualize the system's parts and use the Designation Guide [3] for consistency in documentation. This aids in organizing and tracking components throughout the process.
4. **Estimate Analysis Effort and Resources:** Assess the complexity of the system to estimate time, tools, and resources needed, especially if the system includes multiple interdependent parts to allow a better planning and resource allocation.

5.1.2. Step 2: Analysis (see Fig. 2)

Objective: Conduct a systematic, in-depth examination of the Embodiment Function Relations (EFR) within the system to understand how each component contributes to the overall function.

Follow these Steps:

1. **Identify System States and Integration Points:** Use a System State-Function Diagram (SFD) to identify significant system states and integration points where the system interacts with external elements (e.g., Connectors) to provide a complete picture of the system's functionality across various conditions.
2. **Analyze Embodiment Function Relations:** Apply C&C² analysis tools to map how specific shapes and structures (e.g., WSP and CSS) contribute to the system's functions. This helps identify the purpose and behavior of each part.
3. **Assign Confidence Levels:** Document the confidence levels [2] for each observed relationship or function, noting any uncertainties. This identifies areas that may need further verification or deeper analysis, adding robustness to the findings.
4. **Define Functional Parameters:** Identify key parameters (e.g., forces, dimensions) that are essential to each function. This step allows for measurable outcomes that can inform later stages, particularly synthesis and optimization.

5.1.3. Step 3: Documentation (see Fig. 3)

Objective: Organize and record analysis results in a clear, structured format, enabling easy access, reference, and application in synthesis.

Follow these Steps:

1. **Structure Data in Templates:** Use structured templates to document embodiment parameters, functions, and confidence levels, ensuring consistent formatting and clear, accessible records.
2. **Link Analysis to Models:** Use hyperlinks to connect each part of the documentation to the corresponding C&C² models or diagrams, allowing for easy cross-referencing and verification.
3. **Verify Completeness and Accuracy:** Periodically review the documentation to ensure it accurately reflects all critical aspects of the analysis and that no essential data has been overlooked.

5.1.4. Step 4: Synthesis (see Fig. 4)

Objective: Use the documented analysis to develop, test, and refine potential optimizations, modifications, or enhancements.

Follow these Steps:

1. **Identify Optimization Potentials:** Filter and analyze the documented data to pinpoint areas for improvement, considering both functional and structural refinements.
2. **Search for Reference System Elements:** Identify similar components or configurations used in other systems as benchmarks or inspiration, which can guide optimization or provide alternative solutions.
3. **Formulate and Test Hypotheses:** Based on analysis insights, hypothesize changes or new configurations, then evaluate these hypotheses through simulations or prototyping.
4. **Document Modifications:** Record all proposed and tested modifications for future reference, preserving insights and outcomes that can inform similar studies or designs.

5.1.5. Step 5: Evaluation and Adjustment (see Fig. 5)

Objective: Assess the synthesis outcomes and make any necessary adjustments to improve performance or address issues that emerged.

Follow these Steps:

1. **Evaluate Synthesized Outcomes:** Review and test the modifications or optimizations made in the synthesis phase to confirm they meet performance goals and design specifications.
2. **Identify Issues or Unmet Objectives:** Compare the synthesized outcomes to the original objectives, noting any gaps or areas needing further refinement.

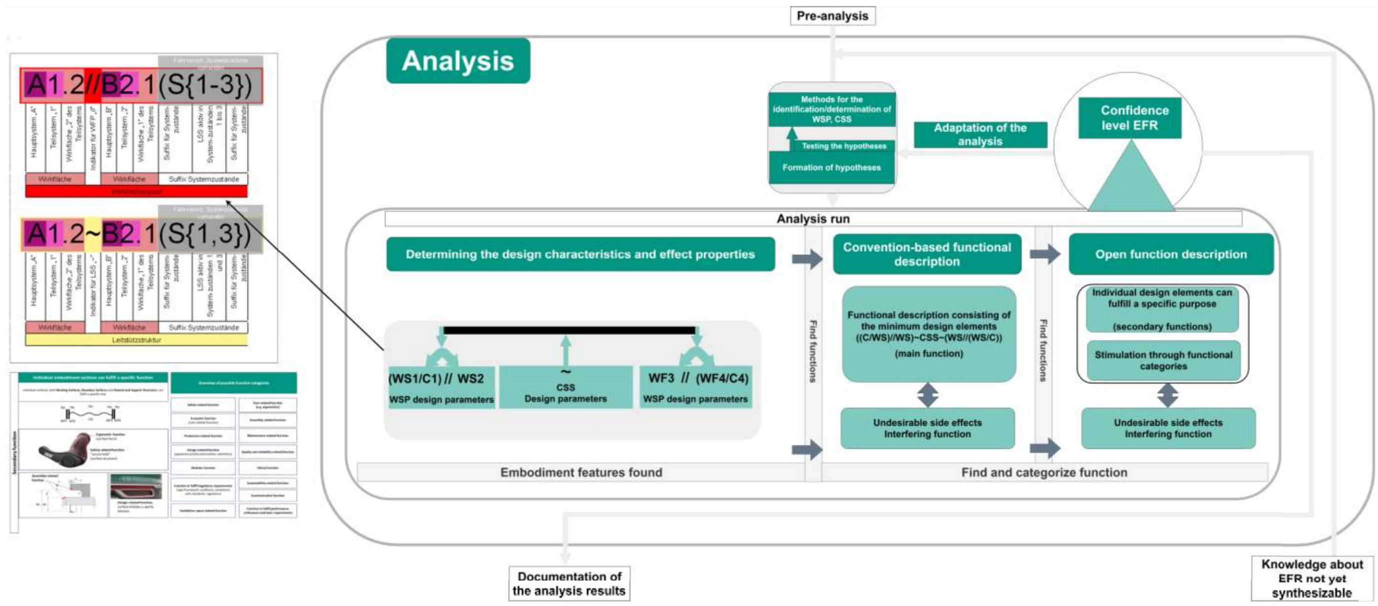

Fig. 2: Step 2: Process of the Analysis (right) and Designation Guide (left top) and overview of possible functions (left bottom)

3. **Make Adjustments:** Modify the design as needed, incorporating feedback or additional insights gained during testing and evaluation.
4. **Final Documentation:** Record all evaluation outcomes, adjustments made, and final design parameters. This step ensures that the final version is thoroughly documented for future reference, verification, or replication.

6. Discussion

This chapter presents a discussion of the results obtained from applying the proposed Process Model in both educational and industrial settings. The focus is on assessing how well the model improved the systematic analysis and documentation of Embodiment Function Relations (EFR).

6.1. Evaluation of the proposed Process Model

The evaluation was conducted in two settings: a Live Lab involving students from KIT and an industrial case study. In both scenarios, the Extended C&C²-Approach was compared with the classical C&C²-Approach to measure improvements in the quality and consistency of EFR documentation. The results indicated that the Extended C&C²-Approach, with its structured templates, led to a more systematic and detailed analysis, enhancing the quality and clarity of the documentation. [6]

6.2. Differences from the existing process model

The proposed Process Model differs from the existing process model of the classical C&C²-Approach [2] in several key aspects. The classical approach primarily focuses on problem analysis and solution generation, while the proposed Process Model emphasizes the systematic documentation of knowledge throughout the product development phases. By integrating elements such as the Designation Guide and Functional Delimitation, the Extended C&C²-Approach formalizes the process of capturing EFR, which was previously ad hoc and inconsistent.

The classical C&C²-Approach also lacked a comprehensive framework for documentation, making knowledge transfer challenging [7]. In contrast, the proposed Process Model includes a dedicated Documentation Phase, which ensures that all captured EFR are consistently labeled and systemati-

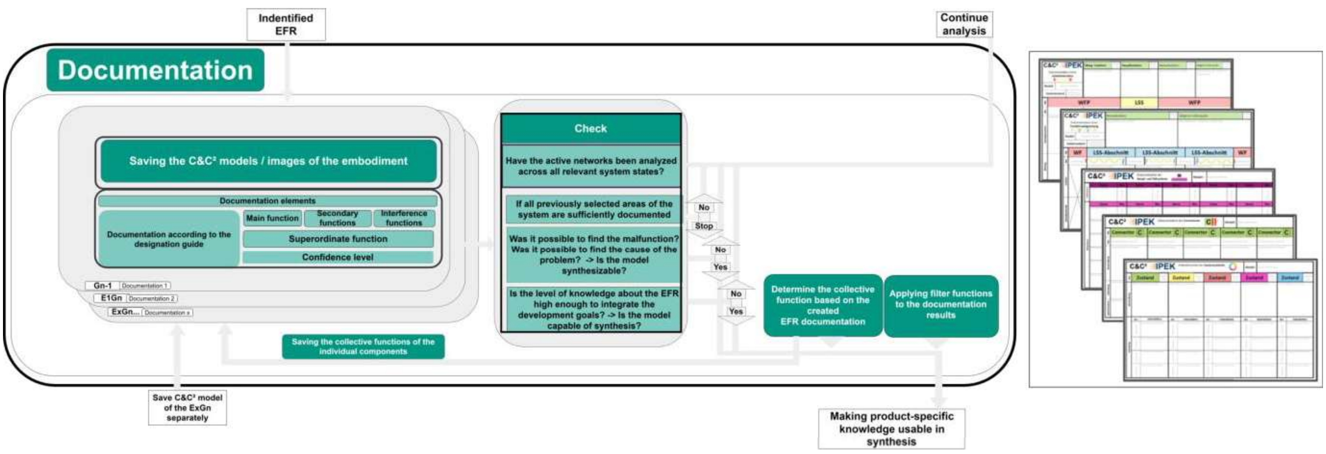

Fig. 3: Step 3: Process of Documentation (left) and documentation worksheets (right) [7]

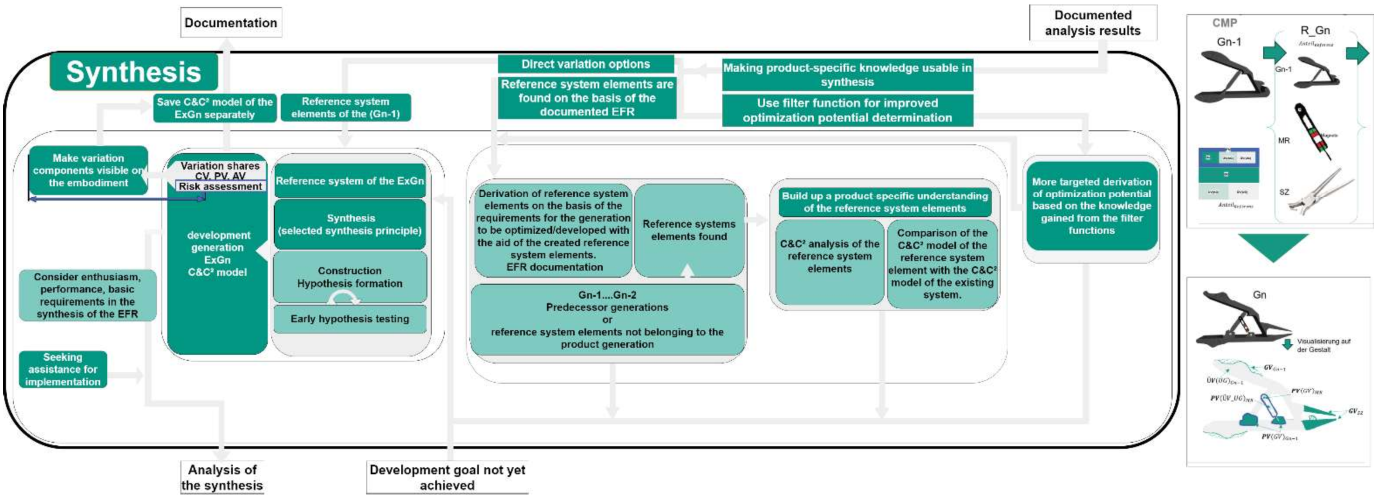

Fig. 4: Step 4: Process of Synthesis with an example of a compliant mechanism plier (right)

cally archived for future use. This focus on structured documentation addresses one of the major limitations of the classical C&C²-Approach.

Another difference is the use of structured templates and predefined workflows to support analysis. The existing process model relied heavily on the experience and intuition of engineers, which led to variability in the quality of analysis across different projects.

6.3. Strengths of the proposed Process Model

The Extended C&C²-Approach offers several benefits. First, the proposed Process Model promotes consistency across different projects by providing standardized tools like the Designation Guide and Functional Delimitation. By systematically identifying all EFR, the proposed Process Model supports a thorough understanding of the product's functionality, thus enhancing both the quality of documentation and the engineering team's capacity for innovation.

The proposed Process Model's documentation phase was found to be especially effective in improving knowledge retention, thereby addressing the challenge of the demographic shift in engineering. The Designation Guide ensured that components were named consistently, reducing the chances of miscommunication across engineering teams. Additionally, the Functional Delimitation tool allowed complex systems to be divided into distinct sections, each serving a specific purpose, improving the focus and effectiveness of the analysis.

6.4. Challenges and Limitations

In this section, we answer research question **RQ2** in regard of the challenges. The answer on how to address those issued is given in the chapter 7.

Despite the advantages, some challenges were identified during the evaluation. The most significant challenge was the additional time required for analysis using the extended templates. While the detailed analysis allowed for a more comprehensive understanding of the system, it also demanded more effort and time. This was particularly highlighted in the industrial case study, where time constraints are a significant factor. [6]

Another challenge was related to training. Both students and practicing engineers indicated that the 20-minute introduction provided for using the Process Model was insufficient. Many participants felt that a more thorough training program would be required to ensure proficiency in applying the extended tools effectively. This underscores the need for comprehensive training materials that provide practical examples and exercises.. [6]

6.5. Key Findings and Insights

The evaluation revealed that the structured Process Model not only enhanced the analysis quality but also significantly improved the retention of product knowledge. The systematic approach ensured that all relevant functions were documented, providing a solid foundation for future product development. However, it also became clear that effective implementation of the Process Model would require balancing the trade-off between detailed analysis and efficiency, particularly for time-sensitive projects.

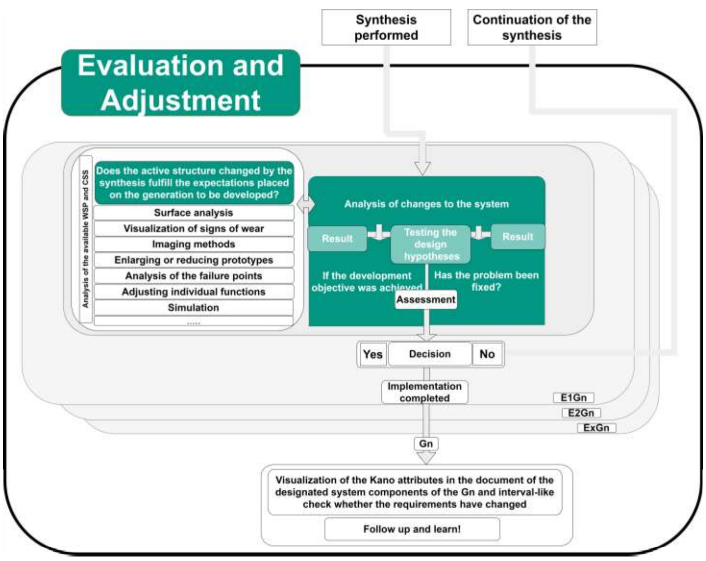

Fig. 5: Step 5: Process of Evaluation and Adjustment

Another key insight was the necessity of a comprehensive training program. Participants reported that with better training, they would be able to fully leverage the extended tools and templates. Therefore, future work should focus on developing in-depth training modules that provide detailed guidance on applying the Process Model.

7. Conclusion and Future Work

The newly developed Extended C&C²-Approach, supported by the proposed Process Model, has shown to improve the systematic analysis and documentation of Embodiment Function Relations (EFR) in both educational and industrial settings. The use of formalized templates and structured tools has provided a clear advantage in terms of the quality and comprehensiveness of the analysis. The enhanced capability to document and utilize EFR systematically is crucial for maintaining the innovative capacity of engineering teams, especially in the face of demographic challenges that lead to the loss of experienced personnel.

For future work, several steps are recommended. First, a comprehensive training program should be developed to support the implementation of the proposed Process Model. This training should include in-depth sessions on how to apply the templates effectively, ensuring that users feel confident in using the Extended C&C²-Approach in practice. Additionally, further research should explore how the proposed Process Model can be adapted to different industries and types of products to assess its generalizability.

Moreover, the integration of digital tools and software to support the documentation and analysis processes could further enhance the efficiency and usability of the proposed Process Model. Automated analysis tools that assist in identifying and documenting EFR could be a valuable addition, reducing the time required for manual analysis and enhancing consistency across different users.

Table 1: Glossary of the terms used

Term	Description
Embodiment Function Relations (EFR)	Interplay between a product's physical embodiment and the functions it performs, often tacitly held by experts. [2]
Working Surface Pair (WSP)	Two surfaces that come into contact to enable or constrain a specific function. [2]
Channel and Support Structure (CSS)	Physical paths or structures enabling or restricting the flow of energy, signals, or matter. [2]
Connectors (C)	Interfaces linking external or internal elements to the system, that are not part of the design space. [2]
Functional Delimitation	Technique for segmenting complex systems into distinct functional sections to clarify roles and interactions.[8]
Designation Guide	A standardized naming convention ensuring uniform labeling and clear identification of system components. [3]

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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.

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