

Integrating Engineering Mechanics into the Contact and Channel Approach for Targeted Embodiment Synthesis

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Abstract

Findings from previous Live Lab studies and practical applications suggest that C&C²-based models support the analysis and communication of existing Embodiment Function Relations, while the derivation of concrete embodiment synthesis decisions often requires additional methodological support. This phenomenon is identified as a Synthesis Gap. Current synthesis heuristics with the C&C²-Approach lack the quantitative precision required to interface directly with the physical principles of Engineering Mechanics. To bridge this gap, this paper proposes a conceptual extension of the Contact and Channel Approach by introducing Working Surface Pair Orientation and Working Surface Pair Area as explicit, quantifiable vectorial attributes. By decomposing functional interfaces into projected spatial components, designers can directly apply mechanical constraints such as friction, force equilibrium, lever arms, and surface pressure to their functional models. The extended methodical procedure and its updated synthesis principles are demonstrated through cases, including a mechanical seesaw and a dynamic safety catcher system. The application illustrates that quantifying these functional attributes supports the transition from intuition-driven geometry generation to systematic, hypothesis-driven embodiment synthesis.

Keywords: Contact and Channel Approach, Embodiment Synthesis, Engineering Mechanics, Hypothesis-driven Design, Working Surface Pair Orientation

1. Introduction

In mechanical engineering design, the systematic transition from abstract functional requirements to concrete embodiment remains a central challenge. Designers must not only determine what functions a technical system should fulfill but also how these functions are physically realized through interacting components and structures. Within this context, the Contact and Channel Approach (C&C²-Approach) has become a widely established methodology for analyzing Embodiment Function Relations (EFR) in technical systems. The C&C²-Approach models Embodiment Function Relations (EFR) using the elements Working Surface Pairs (WSP), Channel and Support Structures (CSS), and Connectors. WSP describe boundary interfaces at which energy, material, or information is exchanged, while CSS connect these interfaces and transmit or store the corresponding system variables. [1–3]

Prior work has demonstrated the usefulness of C&C²-based models for functional analysis, failure analysis, interdisciplinary systems modeling, and the

communication of embodiment-function relations across design teams [3–5,12,13].

Despite these strengths, empirical observations from design education and industrial practice indicate a recurring challenge when the approach is applied to embodiment synthesis. While designers are generally able to model existing technical solutions using the C&C²-Approach, they frequently struggle to derive concrete embodiment design decisions when developing new solutions in early design phases. The approach enables engineers to identify where functional interactions must occur, but provides limited guidance on how the geometry of these interactions should be systematically designed. Consequently, the transition from functional modeling to embodiment often remains heavily dependent on designer intuition. [6,7]

In this paper, the term Synthesis Gap denotes the specific gap within the current C&C²-based workflow between qualitative EFR modeling and the direct use of mechanics-based quantitative reasoning for targeted embodiment synthesis. In particular, recent work argues that current C&C² models do not yet contain enough quantitative data to directly pinpoint forces and comparable physical quantities, and that enriching WSP and CSS with quantitative information could open further synthesis possibilities. [8]

Engineering Mechanics provides well-established mathematical relationships describing how forces, torques, and stresses depend on embodiment properties. However, because these embodiment attributes are not explicitly represented in the current C&C²-Approach modeling framework, designers lack a systematic interface that allows functional models to directly inform mechanical reasoning during early embodiment design. Instead, the transition from functional modeling to mechanical verification is typically performed informally and iteratively, often relying on trial-and-error approaches rather than structured hypothesis-driven embodiment synthesis.

To address this limitation, this paper proposes an extension of the C&C²-Approach that explicitly incorporates quantitative embodiment attributes of WSP. In particular, the concepts of Working Surface Pair Orientation (WSPO) and Working Surface Pair Area (WSPA) are introduced as explicit attributes that allow functional interfaces to be described in terms of vectorial spatial properties. In the scope of this paper, WSPO is initially considered for planar or locally approximated working surfaces. For curved or spatially distributed contacts, the orientation may be represented through local surface normals or discretized surface segments. By representing these attributes within the functional model, it

becomes possible to directly connect C&C²-based system representations with the analytical principles of Engineering Mechanics, such as force equilibrium, lever arms, friction conditions, and surface pressure.

Based on this conceptual extension, the paper introduces extended synthesis principles that support designers in systematically manipulating embodiment parameters during embodiment synthesis. These principles enable hypothesis-driven embodiment synthesis by linking variations in WSPO and area, as well as variations in CSS, to their mechanical consequences.

The methodical procedure is illustrated through two demonstrator cases: a simplified mechanical seesaw system and a dynamic safety catcher mechanism used in hydraulic lifting systems. These cases demonstrate how explicitly representing Working Surface attributes enables designers to systematically derive embodiment synthesis hypotheses and connect functional models with mechanical reasoning.

The proposed extension does not claim to replace established tools of Engineering Mechanics, such as free-body diagrams, equilibrium equations, or stress analysis. Instead, it addresses the preceding modeling step: the translation of C&C²-based functional models into mechanics-readable embodiment parameters. The novelty therefore lies not in the mechanical equations themselves, but in making WSPO, projected area, and CSS dimensions explicit within the C&C² model so that designers can derive mechanics-based synthesis hypotheses directly from the functional representation.

This paper makes three conceptual contributions. First, it identifies a synthesis gap between qualitative C&C²-based functional modeling and mechanics-based embodiment synthesis. Second, it introduces WSPO and WSPA as explicit, quantifiable attributes of WSP. Third, it derives extended synthesis principles that link variations of WSPO, WSPA, and CSS dimensions to expected mechanical consequences.

By providing an explicit quantitative interface between functional modeling and mechanical reasoning, the proposed extension aims to support engineers in systematically translating functional requirements into embodiment decisions during early design phases.

2. Related Work

2.1 Foundations of the Contact and Channel Approach

Embodiment Function Relations (EFR) can be represented through different modeling perspectives in engineering design. In embodiment design, a variety of product models exists, each supporting different modeling purposes and abstraction levels [14]. Established approaches include function structures, physical effect chains, organ structures, function-means modeling, SysML-based system models, and product architecture models. These approaches support different abstraction levels and modeling purposes, ranging from early

functional decomposition to system architecture and behavioral representation. Within this landscape, the C&C²-Approach provides a particularly embodiment-oriented perspective because it explicitly links function fulfillment to concrete physical interfaces and load-carrying structures.

The theoretical foundation of this research is the Contact and Channel Approach (C&C²-A), initially introduced to support the systematic analysis of EFR. The methodology achieves this by decomposing technical systems into three core elements: Working Surface Pairs (WSP), Channel and Support Structures (CSS), and Connectors (C) [1,9].

- WSP: The specific boundary interfaces where components, fluids, or fields touch and interact to transfer energy, material, and/or information.
- CSS: The material volume connecting the Working Surfaces within a component, responsible for the internal transmission of forces and defining the elastic or rigid structural properties.

By abstracting from detailed embodiment models, the C&C²-A enables designers to describe exactly how product functions are physically realized through these element interactions. Prior work demonstrates its high suitability for functional analysis, fault identification, and communication within interdisciplinary design teams [10,11]. In these analytical contexts, the abstraction level of the approach is regarded as a key strength, allowing complex systems to be structured without prematurely constraining the solution space.

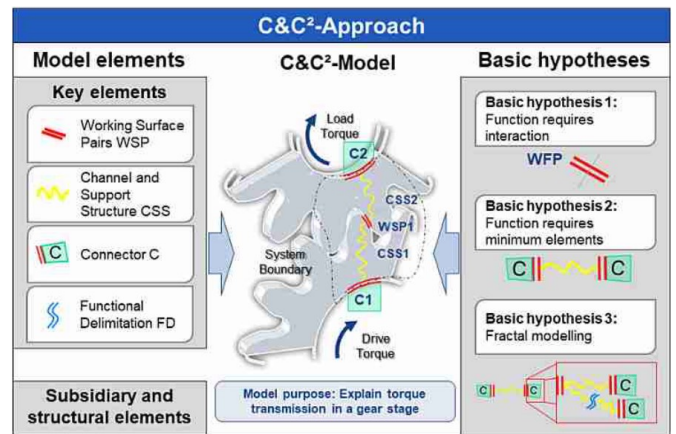


Figure 1: Adapted summary of the C&C²-Approach with adjustments like color code (Working Surface Pair = red; Channel and Support Structure = yellow; Connector = green; Functional Delimitation = blue) and example of Functional Delimitation [6], based on [1]

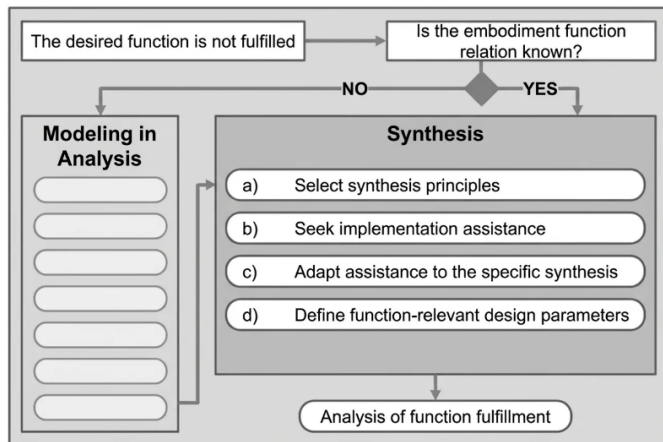


Figure 2: Model building with the C&C² Approach in synthesis, translated from [1]

2.2 Current State of Embodiment Synthesis and Recent Extensions

Despite its methodological maturity in retrospective analysis, targeted embodiment synthesis remains a major challenge when applying the C&C²-Approach. Previous research highlights that designers frequently struggle to derive concrete embodiment decisions from abstract functional models. Currently, the methodology offers specific synthesis heuristics to guide designers, which primarily consist of three operational principles: adding

WSP/CSS, removing WSP/CSS, or modifying the properties of existing WSP/CSS [1].

While these synthesis principles are conceptually sound, they remain predominantly qualitative and rely heavily on the implicit experience and intuition of the designer. To address challenges related to modeling consistency and to better handle complex components, several recent extensions to the C&C²-Approach have been proposed. Notable contributions include an Extended C&C² Approach that introduces a strict Designation Guideline [6,12] and the concept of Functional Delimitation [13]. These extensions intend to reduce ambiguity in functional models and enhance their comparability across system levels.

2.3 The Disconnect from Engineering Mechanics

However, even with these modeling extensions, the fundamental transition from qualitative functional analysis to quantitative embodiment synthesis remains insufficiently supported. Specifically, current C&C²-Approach modeling practices do not explicitly represent the embodiment attributes essential for mechanical reasoning. Quantitative properties, such as the exact spatial orientation and the surface area of the WSP, are typically left implicit under the generalized synthesis principle of "modifying properties" [1,2].

Standard Engineering Mechanics provides well-established mathematical relationships that describe the

physical behavior of mechanical systems. These relationships rely entirely on explicit spatial information: contact areas, normal vectors, and force transmission paths. Because the C&C²-Approach lacks a structured, quantitative interface to provide these spatial parameters, functional models cannot be directly linked to the verification methods of Engineering Mechanics (e.g., stress analysis, friction evaluation, or static equilibrium calculations) during the critical early design phases. Consequently, designers are forced to bridge this gap informally, often reverting to iterative trial-and-error rather than systematic, hypothesis-driven embodiment synthesis.

3. Research Methodology and Objectives

3.1 Problem Statement

Empirical observations from design education, particularly from Live Lab studies on the application and training of the Extended C&C²-Approach, indicate that students and practitioners can generally apply C&C² models for the analysis of existing systems, but require additional support when transferring these models into concrete synthesis decisions [6,7]. This also corresponds to observations from industrial application contexts, where C&C² models are often used to structure and communicate existing Embodiment Function Relations (EFR), while the derivation of new geometry variants remains strongly dependent on individual design experience.

Current synthesis heuristics within the C&C²-Approach primarily suggest qualitative actions, such as adding, removing, or modifying Working Surface Pairs (WSP) and Channel and Support Structures (CSS). However, these principles often lack the quantitative precision required to guide the specific embodiment of mechanical interfaces (e.g., determining exact spatial orientations or surface areas). Consequently, designers lack a structured, quantifiable link between the abstract functional model and the established principles of Engineering Mechanics (e.g., free-body diagrams, force vectors, and stress distribution). This phenomenon is defined in this paper as the Synthesis Gap.

3.2 Research Questions

To address this Synthesis Gap, this research aims to extend the modeling capabilities of the C&C²-Approach, enabling a transition from qualitative functional modeling to quantitative, mechanics-based analysis and, based on this analysis, to more targeted embodiment synthesis. The investigation is guided by the following three research questions (RQ):

- **RQ 1:** Which limitations of the existing, predominantly qualitative synthesis principles of the C&C²-Approach become relevant when designers need to derive mechanics-based embodiment parameters in early design phases?
- **RQ 2:** How can the C&C²-Approach be extended through specific attributes of Engineering Mechanics,

specifically WSPO and WSPA, to support quantitative reasoning for analysis and synthesis?

- **RQ 3:** What could a structured procedure look like that assists designers in applying quantitative Working Surface attributes first for mechanics-based analysis and subsequently for hypothesis-driven embodiment synthesis?

3.3 Research Approach

This paper follows a conceptual methodological research approach. Based on limitations identified in prior literature and empirical observations from Live Lab studies, a mechanics-based extension of the C&C²-Approach is derived and illustrated through two demonstrator cases. The cases are used to demonstrate logical consistency and applicability, but not to provide empirical validation of method effectiveness.

First, the limitations of current synthesis guidelines are evaluated based on existing literature and user studies (RQ 1). Second, the concepts of Working Surface Pair Orientation (German: Wirkflächenpaarorientierung) and Working Surface Pair Area (German: Wirkflächenpaar-Flächeninhalt) are introduced as explicit, quantifiable attributes of the C&C²-Approach meta-model. By decomposing active Working Surfaces into projected vector components along a defined coordinate system, a direct link to mechanical principles such as force equilibrium and friction is established (RQ 2). Finally, a structured procedural model is derived and initially applied in cases, including a mechanical seesaw and a dynamic safety catcher system. These cases illustrate how the explicit quantification of WSPs provides a conceptual basis for more targeted, hypothesis-driven embodiment synthesis (RQ 3).

4. Quantitative Synthesis through Working Surface Attributes

4.1 Requirements for a Mechanics-Based Extension of the C&C²-Approach

To support mechanics-based analysis and synthesis within the C&C²-Approach, the extension must fulfill three requirements. First, it must preserve the established abstraction logic of the C&C²-Approach by remaining compatible with WSP, CSS, and Connectors. Second, it must make mechanically relevant embodiment attributes explicit without requiring a fully detailed CAD model. Third, it must provide parameters that can be directly interpreted in terms of Engineering Mechanics, such as surface normals, projected areas, force directions, lever arms, and surface pressure. Based on these requirements, WSPO and WSPA are introduced as explicit attributes of WSPs.

4.2 The Concept of Working Surface Pair Orientation and Working Surface Pair Area

By explicitly defining the spatial orientation of a Working Surface, designers can rapidly connect the

functional model to core principles of Engineering Mechanics, such as friction, surface pressure, and fluid mechanics. This concept involves decomposing the active working surfaces into projected components along a defined Cartesian coordinate system (x, y, z). The area is quantified and represented as an area vector. If a specific working surface A_{WSP} is decomposed, the resulting vector can be described (see Figure 3).

$$\vec{A}_{WSP} = \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} \quad (1)$$

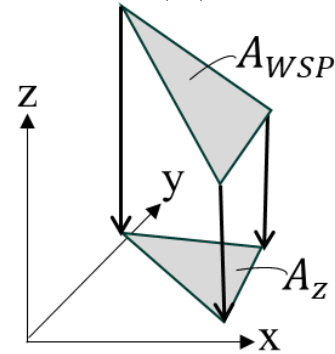


Figure 3: Projection of the Working Surface Pair Area A_{WSP} onto the XY-plane, resulting in the projected area component A_z

The components A_x , A_y , and A_z represent the magnitudes of the projected areas onto the respective coordinate planes, with their directions corresponding to the surface normal vectors. The availability of this quantitative data within the C&C²-Approach model enables designers to analyze mechanical constraints and systematically derive embodiment synthesis steps.

4.3 Extension of the C&C²-Approach Synthesis Principles

Currently, the C&C²-Approach utilizes a generalized synthesis principle of "changing WSP/CSS properties." To provide better guidance for designers during the synthesis phase, we propose detailing and extending these principles based on the newly introduced attributes. We introduce two extended synthesis principles:

- **Variation of WSP Orientation and Area:** In 3D space, this involves adjusting the vector components \vec{A}_{WSP} to alter force transmission angles (e.g., maximizing form-fit or adjusting wedge angles) or scaling the absolute area to influence surface pressure ($p = F/A$). In 2D simplifications, this refers to altering the working surface length.
- **Variation of CSS Volume, Area, or Length:** This principle directly links to the alteration of internal load paths and lever arms, directly impacting bending moments and structural stiffness.

Table 1 C&C²-Approach System Analysis

| WSP, FD, CSS | WSP Orientation, CSS length | Contribution to Function (Mechanics Link) |
|--------------|-----------------------------|--|
| A1//C1 | y | Force transmission from C1 to the axle |
| A2//C2 | y | Force transmission from C2 to the axle |
| A1//A2 | x | Division of the axle into left and right load paths, with force transmission branching from the bearing into the two axle segments |
| A//B | x and y | Force transmission in the x- and y-directions from the axle to the bearing |
| A1~C1 | $l_1 = l_x(A1~C1)$ | Internal transmission of forces, l_x acts as left side lever arm |
| A2~C2 | $l_2 = l_x(A2~C2)$ | Internal transmission of forces, l_x acts as right side lever arm |

4.4 Application Example 1: The Mechanical Seesaw

To illustrate the application of these extended principles, a simplified mechanical seesaw is analyzed (assuming a rigid body with negligible mass compared to applied forces) (see Figure 4). The subsystems and C&C² elements are named according to the designation guideline [12].

System Analysis (C&C²-Approach):

- Identification of the WSPs, CSSs and Connectors.
- Functional delimitation (FD A1//A2) of the axle at the central pivot bearing according to [13].
- Identification of the CSS lengths ($l_1 = l_x(A1~C1)$ and $l_2 = l_x(A2~C2)$) connecting the pivot to the outer WSPs.
- Identification of the applied forces and WSP orientations.
- Functional description (see Table 1).

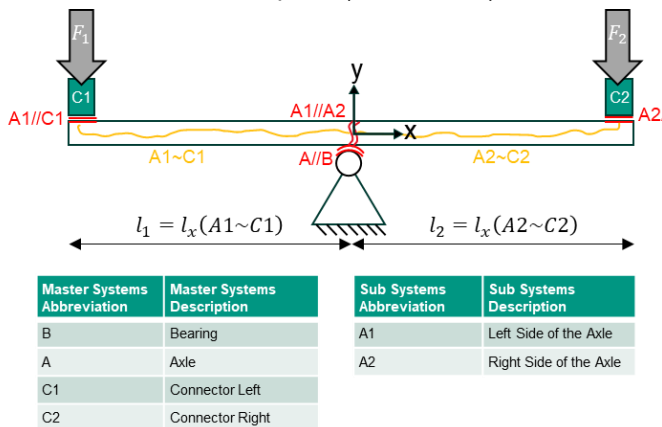


Figure 4: C&C²-Model of the seesaw with decomposition and designation of the (sub-)systems, identification of the WSPs and CSSs

By applying a free-body diagram and considering the lever arms and acting forces, the following analytical expression in the center of the axle is obtained:

$$M_{Center,z} = F_{1,y} \cdot l_1 - F_{2,y} \cdot l_2 \quad (2)$$

Using the extended synthesis principles, specific embodiment hypotheses can be generated:

- Variation of CSS Length: Extending the length l_2 increases the lever arm (see top Figure 5). According to the analytical moment expression, the seesaw will tilt downward on the right side under identical applied vertical forces.
- Variation of WSP Orientation: If the WSP A1//C1 is inclined (see bottom Figure 5) and the force F_1 acts perpendicular to the WSP, the axle moves downward on the right side. The effective torque changes because of a decreasing force $F_{1,y}$.

4.5 Application Example 2: Safety Catchers

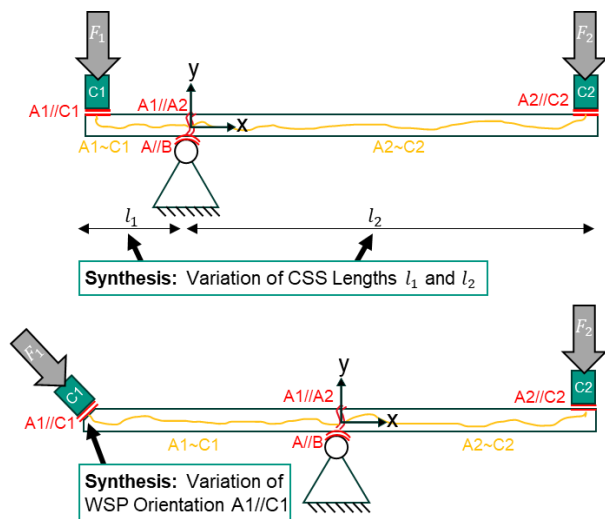
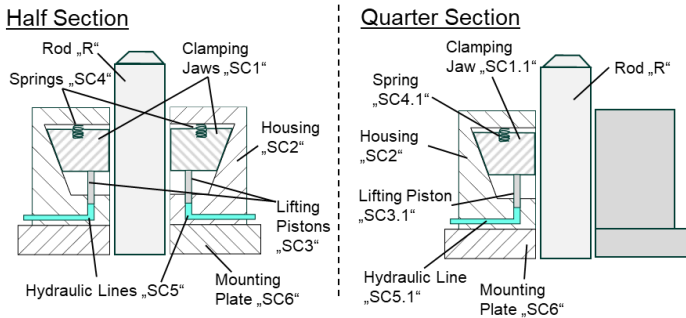


Figure 5: Synthesis proposals for the seesaw with C&C²-models: variation of the CSS lengths (top) and variation of the WSP orientation (bottom)

A more complex industrial application is the safety catcher system (see Figure 6), used in hydraulic lifts to prevent a rod from falling in the event of a pressure failure. The system utilizes several friction wedges to decelerate the rod. The subsystems and C&C² elements are named according to the designation guideline [12]. In the following, a simplified quarter section of the system is considered (see right side Figure 6).



| Master Systems Abbreviation | Master Systems Description | Sub Systems Abbreviation | Sub Systems Description | Amount |
|-----------------------------|----------------------------|--------------------------|-------------------------|--------|
| R | Rod | SC1 | Clamping Jaws | 4 |
| SC | Safety Catchers | SC2 | Housing | 1 |
| | | SC3 | Lifting Pistons | 4 |
| | | SC4 | Springs | 4 |
| | | SC5 | Hydraulic Lines | 4 |
| | | SC6 | Mounting Plate | 1 |

Figure 6: Safety catchers model in the disconnected state with designation of the (sub-)systems: left in half section, right in quarter section

Four distinct functional states are distinguished and named according to the naming convention ('S1'-'S4'):

- S1 (Disconnected State): No safety engagement; wedges do not contact the rod. The rod moves with velocity v_{rod} .
- S2 (Active State, Sliding): Wedges contact the rod; the WSP R//SC1.1 is active with sliding friction. Normal force is amplified by the wedge geometry.
- S3 (Active State, Fixed): The WSP R//SC1.1 is active with static friction; the rod is fully secured ($v_{rod} = 0$).
- S4 (Active State, Overload): The static friction in WSP R//SC1.1 is exceeded; the rod slips but is decelerated.

Figure 7 shows the states S1, S2 and S3. By analyzing the WSP Orientation and Area (see Table 2), designers gain

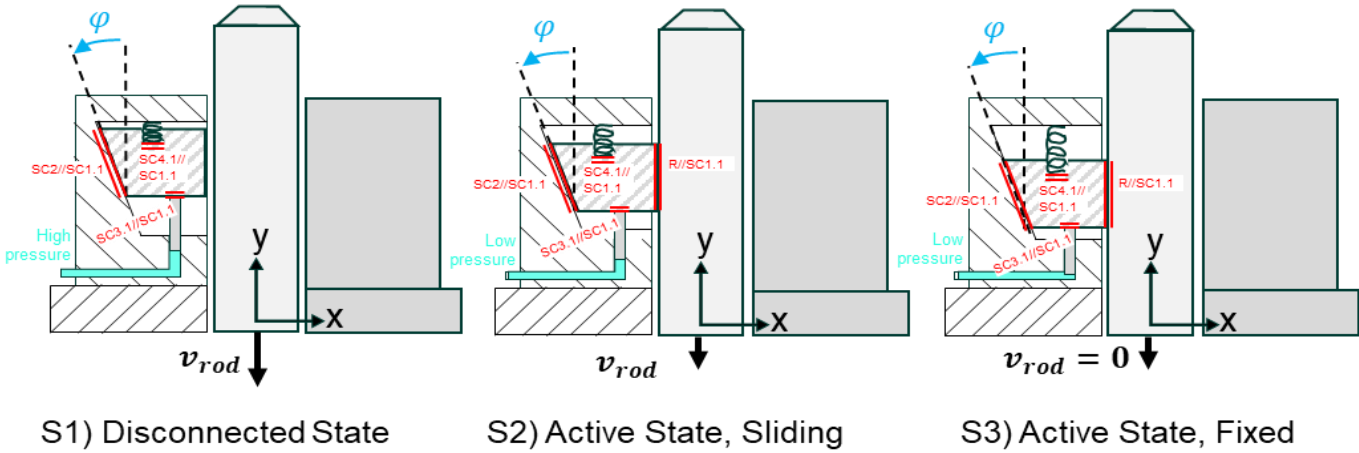


Figure 7: C&C²-Models of states S1–S3 in the quarter section of the system

precise insights into the embodiment drivers of the system's function

Applying the Extended Synthesis Principles, the designer can now hypothesize embodiment variations:

- Variation of WSPO of the WSP SC2//SC1.1: By varying the angle ϕ , the braking behavior can be adjusted. This changes the ratio of A_x to A_y of the WSP SC2//SC1.1. This determines the kinematic constraint of the wedge and directly influences the resulting normal force at R//SC1.1.
- Variation of WSPA of the WSP R//SC1.1: Scaling the surface area $A_{x,R//SC1.1}$ allows the designer to control the surface pressure, thereby preventing material yielding under high loads during state S3 (Active State, Fixed) or S4 (Overload).

4.6 Initial Methodical Procedure for Mechanics-Based Analysis and Targeted Synthesis

Based on the introduced attributes, an initial methodical procedure is proposed. The procedure is not intended as a fully validated design method, but as a structured sequence of modeling and reasoning steps that supports designers in linking C&C² models to mechanics-based analysis and synthesis:

- Extended System Analysis with C&C²-Approach: Establish a relevant coordinate system (2D or 3D). Identify and quantify the WSP Orientation (vector components) and Areas. Determine relevant CSS Volume, Area, or Length.
- Mechanical Mapping: Establish analogies to Engineering Mechanics (e.g., utilizing CSS lengths as lever arms, using WSP area components to construct free-body diagrams).
- Hypothesis-driven Embodiment Synthesis: Apply the extended synthesis principles ("Variation of WSP Orientation/Area" and "Variation of CSS

Volume/Area/Length") to systematically manipulate the embodiment parameters to achieve the desired functional behavior.

The proposed procedure therefore is expected to support a structured transition from functional modeling to geometry generation by explicitly linking working surface attributes to mechanical reasoning.

5. Discussion

With regard to RQ 1, the analysis indicates that the existing synthesis principles provide useful high-level operations, such as adding, removing, or modifying WSPs and CSSs. However, they do not explicitly distinguish mechanically decisive embodiment parameters, such as WSPO, projected area, and CSS length. As a result, they can indicate that a property should be modified, but they provide limited support for deciding which parameter should be varied and what mechanical consequence this variation is expected to produce.

The research presented in this paper addresses the identified gap between qualitative C&C² modeling and mechanics-based reasoning. By introducing WSPO and WSPA as explicit attributes, the approach supports both quantitative analysis of existing Embodiment Function Relations and the derivation of hypothesis-driven synthesis steps. In this sense, the proposed extension does not replace the established C&C²-Approach, but adds a quantitative layer that connects WSP and CSS models to selected principles of Engineering Mechanics.

A major strength of this proposed extension is its reliance on Engineering Mechanics. The concepts of force vectors, surface pressures, and moment equilibrium are universally understood by mechanical engineers. The demonstrator cases, including the mechanical seesaw and the safety catcher system, reinforce the assumption that explicitly mapping these mechanical principles to WSP provides a structured pathway for targeted embodiment synthesis. An extensive and precise analysis of the system using the C&C² Approach remains a fundamental prerequisite for this targeted synthesis, as accurately identifying the active surfaces is necessary before any vectorial attributes can be assigned.

The proposed extension focuses specifically on geometrical and spatial attributes of WSP, namely orientation and area. It does not aim to provide a complete description of all mechanically relevant surface properties [1]. Further attributes such as roughness, material pairing, coating, lubrication condition, hardness, or temperature-dependent behavior remain outside the scope of this paper. However, the proposed attribute-based logic could provide a basis for integrating such properties in future extensions.

By explicitly defining the WSP Orientation and Area as vectorial components, the methodology transforms a previously implicit and experience-driven heuristic into a calculable, systematic synthesis step. This methodical procedure is intended to systematically guide designers, reducing the cognitive load required to translate a functional requirement into a spatial geometry.

Despite these promising conceptual advantages, the current state of the research presents certain limitations. The initial procedural model was applied to illustrative cases to demonstrate its feasibility and logical consistency. However, the resulting impact on the design process has not yet been quantitatively measured. A comprehensive empirical validation regarding how much this extended methodology improves the speed, quality, or physical accuracy of the synthesis steps performed by actual designers is pending. Measuring these human-centric performance metrics within a controlled design experiment is a necessary next step to fully validate the proposed methodical procedure.

6. Conclusion and Outlook

This paper presented an initial methodical procedure to bridge the Synthesis Gap in the Contact and Channel Approach by integrating quantitative principles of Engineering Mechanics. By explicitly defining WSPO and WSPA, the methodology provides a structured pathway from qualitative functional analysis to targeted embodiment. While the application to the presented cases demonstrates the logical consistency and potential of the extended synthesis principles, the results have not yet been empirically quantified. Comprehensive experimental

Table 2: C&C²-Approach System Analysis Categorized by WSP

| WSP | Orientation | Surface Area | Contribution to Function (Mechanics Link) |
|--------------|----------------------|--|---|
| R//SC1.1 | x | $A_{x,R//SC1.1}$ | Generates friction between the wedges and the rod to decelerate the rod in the y-direction. The WSP is active in states S2, S3, S4. |
| SC2//SC1.1 | x, y (Angle ϕ) | $A_{x,SC2//SC1.1}$, $A_{y,SC2//SC1.1}$ | Defines the position of the wedges relative to the housing; wedge angle dictates the conversion of vertical motion into the necessary normal force in the x-direction. The WSP is active in all states. |
| SC3.1//SC1.1 | y | $A_{y,SC3.1//SC1.1}$ | Transmits force in the positive y-direction from the piston to the wedge to disengage the system. Ensures displaceability in the x-direction to prevent jamming. |
| SC4.1//SC1.1 | y | $A_{y,SC4.1//SC1.1}$ | Spring interface; ensures continuous application of preload force in the y-direction. The WSP is active in all states. |

validation to measure the direct impact of the methodical procedure on design efficiency and outcome quality within a controlled engineering environment remains a critical subject for future research.

Furthermore, future research will focus on scaling this quantitative methodology to highly complex, dynamic tribological systems. A primary candidate for this advanced application is the phenomenon of clutch judder. Clutch judder is not merely a surface friction issue but a complex interaction between interfacial adhesion and the internal structural mechanics of the friction lining. Utilizing the extended methodical procedure conceptualized in this paper, these dynamic surface effects can be decomposed into manageable base functions and vectorial components.

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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 Gemini, 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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