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A new approach to derive variation shares by combining the C&C² approach and the PGE model

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Abstract

This paper introduces a method to derive variation shares in engineering design, merging the Contact & Channel Approach (C&C²) with the model of PGE - Product Generation Engineering. It focuses on one-piece parts, enhancing precision in identifying component variations. The integration allows for detailed qualitative modeling and subcomponent analysis, improving design efficiency and innovation, illustrated with bottle examples. This research advances engineering design by enabling more accurate categorization of system variations.

Keywords: embodiment design, systems engineering (SE), design methods, design methodology

1. Introduction

Qualitative design approaches are widely recognized in both academic and industry circles for their ability to facilitate early-stage design exploration and evaluation without detailed numerical analysis. These methods enable designers to swiftly assess various design alternatives. However, the increasing complexity of today's products and systems demands more sophisticated qualitative modeling techniques. We, therefore, focus on applying the Contact & Channel Approach (C&C²) and the Product Generation Engineering (PGE) model to not only mechanical assemblies but also to more granular components. This research explores the combined potential of C&C² and PGE to enhance our understanding of design variations and their implications on system performance.

The synergy between C&C² and PGE was chosen due to their complementary strengths in modeling design variations and tracking design evolution, offering a robust framework for a deeper analysis of engineering systems (Grauberger et al. 2020). This combination is especially pertinent to modern engineering challenges, where integrating form and function with design evolution is crucial. Our choice is rooted in both the theoretical and practical merits of these methodologies, aiming to provide an innovative yet practical solution to current design challenges.

2. State of the art

The exploration of qualitative models in engineering design has become increasingly important as we seek to improve design thinking and knowledge management in the face of increasing system complexity. The design of technical systems is one of the most challenging mental tasks, as it frequently involves complex systems with numerous dependencies and interactions (Hacker 1997). It includes employing primarily creative skills to provide technical resolutions to social demands (Birkhofer 2011). Achieving the intended functionality of a technical system requires accurately defining embodiment features according to functional requirements. The correspondence between a system's desired behavior and its embodiment features is often inferred intuitively, based on assumptions made by the design engineers. (Blessing and Chakrabarti 2009). Both qualitative and quantitative models play critical roles in the design process, although quantitative models have traditionally received more attention. However, qualitative models provide indispensable support in unravelling the complexity of the design process, enabling designers to more deeply understand the relationships between function and embodiment. (Grauberger et al. 2022). Designers can benefit from their advantages if provided with structured guidelines and digital tools since these models don't require a quantitative product specification. There are significant efforts for general modelling, but they primarily focus on computer-based, quantitative models and offer minimal assistance for qualitative modelling (Grauberger et al. 2022). This oversight highlights a gap in the literature and practice, and underscores the need for a more balanced approach that equally values qualitative insights.

The distinction between design methods and tools further elaborates on how specific results are achieved within the design process, from information presentation to task decomposition.

- **Design Method:** *"A specification of how a specified result is to be achieved. This may include specifications of how information is to be shown, what information is to be used as inputs to the method, what tools are to be used, what actions are to be performed, and how the task should be decomposed and how actions should be sequenced."* (Gericke et al. 2017)
- **Design Tool:** *"An object, artifact or software that is used to perform some action (for example, to produce new design information). Tools might be based on particular methods, guidelines, processes or approaches or can be generic environments that can be used in conjunction with many methods."* (Gericke et al. 2017)

Design tools help to streamline parts of the development course and are very valuable but cannot replace the creative process in the designer's mind. As per definition they still are tools and can only assist the process. On the other hand, design methods help structure the process and manage information. Consequently, a wide variety of methods has been developed by researchers over the years to support creative processes of designers and engineers. Blessing and Chakrabarti summarize notable examples of design methods: TRIZ (Altschuller 1984), Axiomatic Design (Suh 1998), Theory of Synthesis (Tomiyama et al. 2002), General Design Theory (Yoshikawa and Man-Machine Communication in CAD/CAM 1981), CPM-Theory (Weber 2005) as well as the Design Research Methodology DRM (Blessing and Chakrabarti 2009). Despite such extensive research effort, methods are not always used in a conscious and structured way and still struggle to provide truly interdisciplinary support (Eigner et al. 2014).

The advent of additive manufacturing and computer-aided design has ushered in an era where generative, topology-optimized, and compliant unibody parts are increasingly common, complicating the intuitive derivation of embodiment function relations. Our research ambitiously extends beyond traditional boundaries to address these modern challenges, emphasizing the need for qualitative design methods that can adeptly navigate the complexities of monolithic components and compliant mechanisms.

The decision to use the C&C² approach and the PGE methodology is based not only on their specific merits, but also on a deliberate effort to bridge the identified gap in interdisciplinary support within design research. The C&C² approach, known for its detailed modeling characteristics, complements the PGE methodology's focus on capturing and managing design evolution. This strategic combination aims to unlock the complexity of modern design challenges while providing a deeper understanding of iterative design processes. To better understand our work within the broader field, we will delve into the nuances of the C&C² approach and highlight its recent advances, including naming guidelines and functional delineation. These elements underscore the approach's adaptability to complex design scenarios, making it an ideal counterpart to the PGE model's systematic handling of product generation variations.

2.1. C&C² approach

For more detailed understanding of the Embodiment Function Relation (EFR), the Contact & Channel-Connector-Approach (C&C² approach) provides important support during the creative process. It provides a structured method to assist designers with the analysis and synthesis of technical systems

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(Birkhofer 2011, 204). In particular, the approach addresses the need to link a product's features to its embodiment and physical design (Albers and Wintergerst 2014, 151). The approach achieves this with the help of following modelling elements: (Matthiesen, 421)

- **Work-Surface-Pairs (WSP)** are surface elements. They are formed when two arbitrarily shaped surfaces of solid bodies or generalized interfaces of liquids, gases or fields come into contact and are involved in the exchange of energy, matter and/or information.
- **Channel-Support-Structure (CSS)** are volume elements. They describe volumes of solids, liquids, gases, or field-permeated spaces that connect exactly two pairs of effective surfaces and enable conduction of substance, energy, and/or information between them.
- **Connectors (C)** integrate the effect-relevant properties that lie outside the design domain into the system consideration. They are an abstraction of the system environment relevant to the description of the function under consideration. Connectors have a representative effective area and an associated model of the relevant system environment and thus lie in the space under consideration but not in the current design space.

2.1.1. Designation guideline for model elements of the C&C² approach

The proposed C&C² approach designation guideline offers improved usability for the approach, by devising a standardized naming and ID system for elements of the approach.

- The designations reveal a structured approach to categorizing various components within a system. In this guide, each main system is assigned a letter, serving as an identifier. This letter denotes the primary function or location of the system within the overall structure. This simple method allows for quick recognition and reference to major parts of a larger system.
- Subsystems are more specific parts within a main system and are denoted numerically. The numbering isn't arbitrary; it establishes a clear hierarchy and relationship among the components. For example, a subsystem labelled as '1.1' indicates not only its primary affiliation with the first main system but also its position or role within that system.
- The guide introduces a way of representing interactions between different parts of the system. Working Surface Pairs (WSPs) and Channel-Support-Structure (CSSs) are identified by specific symbols, like double slashes '//' and tildes '~', respectively. These symbols provide insights into how different parts of the system interact or connect with each other. For instance, a WSP represented by 'F1.1//F2.2' would indicate a functional interaction between two specific subsystems.

Therefore, it provides a comprehensive approach to understanding how various components are organized, how they relate to each other, and how they function together within the larger system. This methodical approach is especially valuable in technical fields where precise identification and understanding of each part's role are essential for analysis, design, or troubleshooting. (Tröster et al. 2023a)

2.1.2. Functional delimitation for modelling in greater detail

Functional Delimitation in the C&C² approach addresses the challenge of modelling complex unibody systems where a single component or structure serves multiple functions or a CSS changes its properties along its way to fulfil different functions A simplified example is given in a screw spring (see Figure 1). This concept is especially relevant in single-piece parts and compliant mechanisms. The approach involves dividing CSS into functionally distinct sections, each performing a specific role. This segmentation enhances the model's accuracy in representing real-world systems. For example, in a body joint, different parts of a structure can perform various functions like support or movement. Functional Delimitation allows for a more detailed and accurate representation of these diverse functions within a unified model, improving understanding and communication in product development and design.

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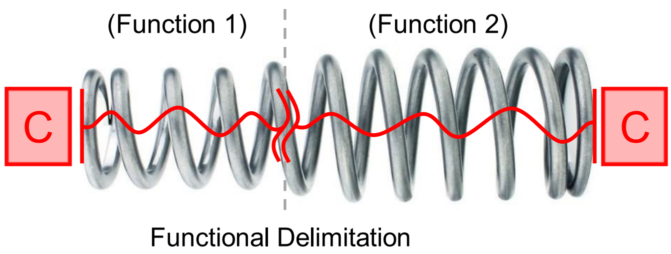

Figure 1. Functional delimitation in a screw spring (Tröster et al. 2023b)

2.2. Model of SGE - System Generation Engineering and the model of PGE

The model of PGE - Product Generation Engineering coordinates the development process of technical systems by formally defining types of variations that differentiate new products from prior products. New product generations are frequently based on knowledge from preceding reference products. Managing this information is crucial for successful development process, therefore PGE offers structured understanding. To describe new generations, the following types of variations can be used (Albers et al., 18)

- **CV: Carryover Variation** (sometimes referred as adoption variation), is conducted through the transfer of partial systems, i.e., existing solutions of reference products or component suppliers are to the new product generations. *"Constructive adaptations are to be minimized, if possible."* (Albers et al., 18)
- **PV: Principle Variation** refers to the development of specific functional units using a new solution principle (compared to reference products). For this process, it is investigated, how the function can be fulfilled in other contexts. Here designers are encouraged to conduct *"systematic search for alternative solution principles using e.g. construction catalogues or creativity techniques"* (Albers et al., 18).
- **EV: Embodiment Variation** is a new development of a partial system through small adjustments of the product embodiment, based on known (and established) solution principles. Embodiment Variation represents the most frequent activity of product development and a highly creative and complex process. *"An example is the enormous increase in the power density of gear drives by an optimization of flank geometry, material, state of the material, production process, and lubrication."* (Albers et al., 18)

Subsequently the PGE allows documentation of information management and identification of variation types during the product development process. The method introduces Product generations Development generations. According to Albers (Albers et al. 2019), an anticipated technical system goes through iterative development stages in order to get from the system of objectives to the object system. The system of objectives in product development contains all relevant targets, their interactions, and constraints necessary for developing the right product. The action system consists of structured activities, methods, and processes. It is used to transfer the target system to the object system and contains all the resources required to realize product development. The object system describes the product after completion of the development process, including all partial solutions that arise during the development process (Albers et al. 2019).

2.3. Connection PGE & C&C² approach

A first attempt explored the integration of the C&C² approach with the model of PGE - Product Generation Engineering, focusing on principle, embodiment, and Carry-over Variations. As a result, it was indicated, that Principle Variations altered the number of Working Surface Pairs (WFPs) and Channel Support Structures (CSS), posing significant challenges and necessitating extensive validation. Embodiment Variations was able within existing structures, changing the shape and arrangement of components without adding or removing elements. Carry-over Variations mainly affected connectors, maintaining the core structure. (Albers et al. 2017)

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3. Methodology

Addressing the challenge of accurate determination of variation shares in component properties, in particular for products with evolving characteristics, requires a methodological approach that is both robust and flexible. To address this challenge, this work integrates the Product Generation Engineering (PGE) model with the advanced Contact & Channel Approach (C&C²), with an emphasis on functional delimitation.

The methodological framework is designed to be adaptable to a range of product complexities, from simple to more complex designs. The selection of examples, ranging from bottles to compliant grippers, provide increasingly complex case studies to demonstrate the applicability and scalability of our approach. Each example was chosen for its relevance to typical engineering challenges and to illustrate the nuanced application of PGE and C&C² principles in practical scenarios.

Given the sensitivity and proprietary nature of some projects, we address confidentiality constraints by focusing on generic examples that still provide substantive insights into our methodology. This approach ensures that we maintain the integrity and applicability of our research while respecting confidentiality agreements.

Through detailed analysis of these examples, we apply the principles of PGE and C&C², and gain valuable insights that improve our precision in identifying variation shares. This iterative process, informed by both theoretical frameworks and practical applications, led us to formulate the following research questions:

- **RQ1:** How can the C&C² approach be better integrated with the PGE model to address complex design challenges effectively?
- **RQ2:** How can the determination of variation shares be refined to increase its accuracy and applicability in engineering design?
- **RQ3:** What quantitative measures do exist to quantify variation shares and how do they differ?

To systematically address these questions, our methodology involves a structured analysis that includes the following steps:

- Identification of key components and interfaces within the product examples using the C&C² approach. This step is essential to establish a baseline for functional analysis and variation share determination.
- Apply Functional Delimitation to further segment the components and improve our understanding of their individual and collective roles within the system.
- Use the PGE model to track the evolution of these components across design iterations, allowing us to determine where and how variation occurs.
- Comparative analysis of variation shares derived from this methodology with traditional methods, highlighting the precision and insight gained from our approach.

This methodology not only advances our theoretical understanding of design variation, but also provides a practical framework for engineers and designers to apply in their work, bridging the gap between theory and practice.

Our findings and the insights derived from the application of this methodology are presented in the following sections, with particular emphasis on the results, discussion, and summary outlook. Through this comprehensive analysis, we aim to make a meaningful contribution to the field of engineering design by offering new perspectives and methodologies for addressing some of the most pressing challenges in the discipline.

4. Results

The investigation of the application of the Contact & Channel Approach (C&C²) with the Functional Delimitation integrated with the Product Generation Engineering (PGE) model provides insightful results, particularly in the context of identifying and quantifying variation shares within system components.

For the initial case study, we compare two bottle variants (Variant A and Variant B, see Figure 2). The comparative analysis of the two variants, with and without the application of Functional Delimitation,

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reveals a differentiated understanding of the variation shares. Initially, a simple examination suggests 100 percent embodiment variation between the two variants (see Figure 2, left). However, the application of Functional Delimitation allows to identify three areas of Carryover Variation and one area of Embodiment Variation, providing a more refined analysis (see Figure 2, middle). This subdivision not only underscore the importance of detailed component analysis, but also demonstrated the method's ability to capture subtle design variations.
A different approach is to divide in terms of surface area sections, length or volume sections (see Figure 2).

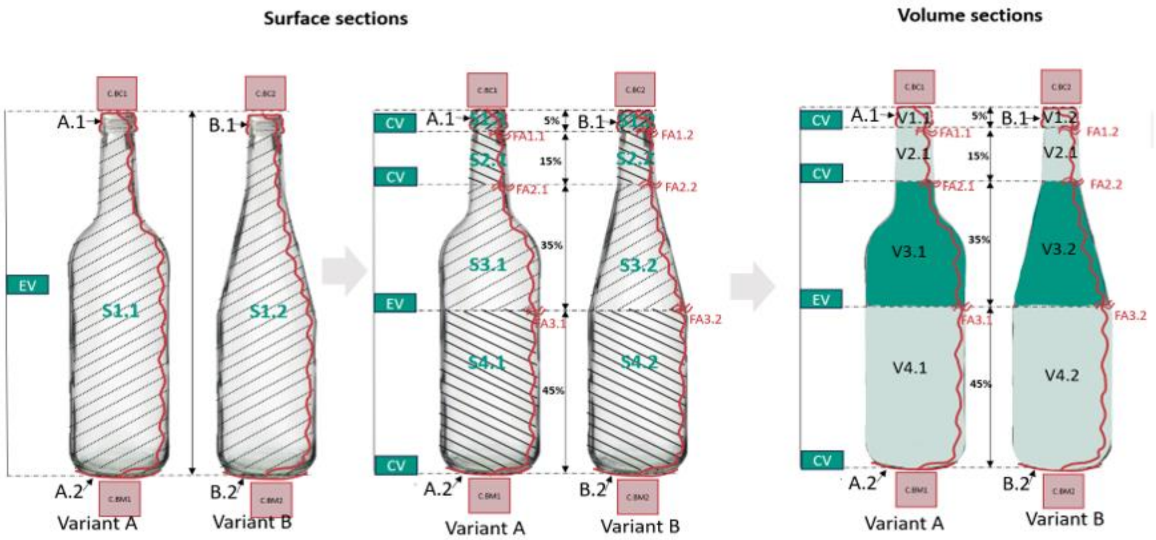

Figure 2. Sections (left without Functional Delimitation), (middle with Functional Delimitation) as surface sections and volume sections (right)

In all of the illustrations, it is immediately apparent that subdividing the shape into individual sections results in a significant gain in information. If the shape is not subdivided, then there is a one hundred percent Embodiment Variation between Variant A and Variant B. However, if the bottles are subdivided into shape sections with the help of the Functional Delimitation, different proportions of variation can be clearly determined. If we look at the sections delimited by horizontal dividing lines and simply count them, we obtain a division of the system components into 75 percent Carry-over Variation and 25 percent Embodiment Variation (see Figure 3). If, on the other hand, the sections are subdivided according to length and their proportion of the overall shape is determined, we obtain a breakdown of 65 percent Carry-over Variation and 35 percent Embodiment Variation. If the length of the CSS is considered and compared between the two Variants, it can be seen that the length of the CSS has decreased by 20 percent in the Embodiment Variation section.

Shape sections -> Proportion of variation	Counting the variation parts	Change in length of the CSS -> (functional delimitation)
65% CV	CV 75 %	CV Variant A to B 0%
35% EV	EV 25 %	EV Variant A to B -20%

Figure 3. Percentages of the variations

Similar methods were applied to the case of a compliant unibody mechanism. In this case we took a design of a compliant gripper (Hedge and Ananthasuresh 2009) with the objective to optimize the gripper in further generations with help of PGE and C&C2 Approach to reduce stress (see Figure 4).
As none of the author has significant experience with the design of compliant mechanisms, first intuitional variations in embodiment lead to worse performance.

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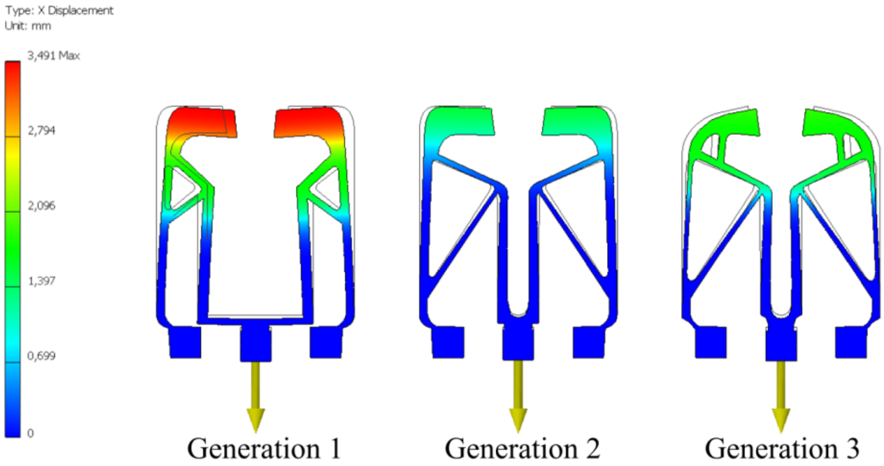

Figure 4. Intuitive attempts of gripper modification

Consequently we tried to apply C&C2 for analysis of the elements of the embodiment and conducted the functional delimitation of the gripper (see Figure 5). This helped us decode the design and create next generation of the gripper which is made of less material and performs its main function without any significant decrease in its effectiveness.

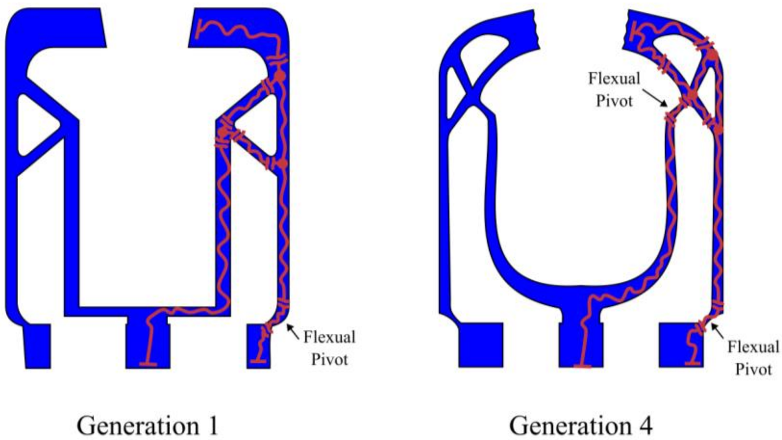

Figure 5. Development of Generation 4 with help of C&C2 Approach

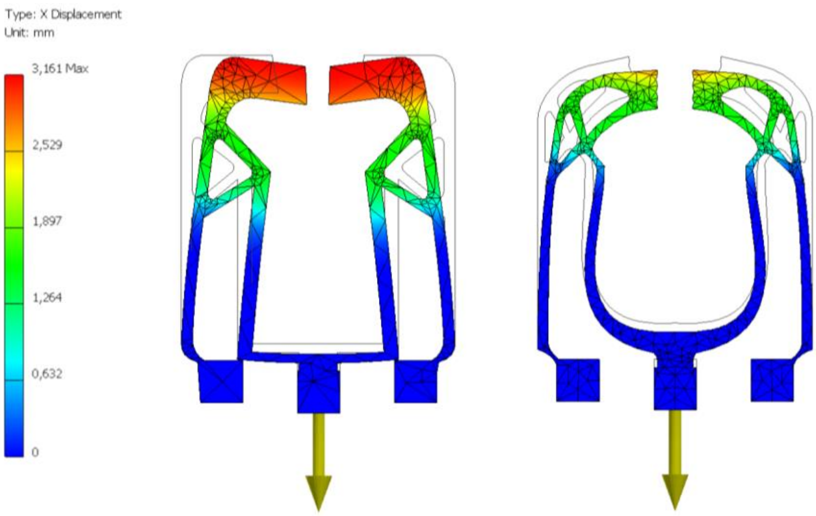

Figure 6. Load simulation for validation of the desired deformation

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5. Discussion

The integration of the Contact & Channel Approach ($C\&C^2$) with Functional Delimitation and the Product Generation Engineering (PGE) model not only revealed the complexity of design variations in the bottle examples, but also demonstrated its applicability to more advanced engineering challenges, such as the optimization of a compliant gripper mechanism. This diversity of application underscores the adaptability and precision of the methodology in dissecting and analyzing engineering systems across domains. For the bottle variants, our methodology's ability to detect and quantify variation shares led to a nuanced understanding of design changes, highlighting the importance of detailed component analysis. Similarly, the gripper case study extended this analytical depth into the realm of compliant mechanisms. Initially, intuitive design adjustments resulted in suboptimal performance, highlighting the need for a systematic approach to design evolution. The application of $C\&C^2$ and Functional Delimitation to the gripper analysis facilitated a strategic redesign that reduced material usage without compromising functionality. This process was validated through load simulation, confirming the effectiveness of our methodology in improving the gripper's design while maintaining its essential function. Such results demonstrate the method's ability not only to identify subtle design variations, but also to make informed decisions to optimize product performance. This juxtaposition of case studies-from the simplicity of bottle variations to the complexity of compliant mechanisms-illustrates the broad applicability of our approach. It shows how Functional Delimitation, combined with the analytical power of $C\&C^2$ and the evolutionary perspective of PGE, can make a significant contribution to the field of engineering design. This methodological synergy enables designers to navigate the intricacies of modern product development with greater accuracy and confidence. The successful optimization of the gripper, guided by our integrated approach, suggests a promising avenue for future research. It demonstrates the potential of this methodology to address not only the aesthetic or functional aspects of design, but also to improve the structural efficiency and performance of complex mechanisms. Further research is needed to extend the applicability of these methods to a wider range of engineering challenges, possibly incorporating advanced computational tools and algorithms to automate and refine the analysis process.

In summary, the results of both case studies confirm the value of combining $C\&C^2$, Functional Delimitation, and PGE in engineering design. This integrated approach not only enriches our understanding of design variation, but also enables us to make more informed, data-driven decisions in product development. As we continue to refine these methodologies, their contribution to advancing design accuracy and innovation in engineering is undeniable.

6. Summary and outlook

This research has demonstrated the profound impact of integrating the $C\&C^2$ approach with functional delimitation and the Product Generation Engineering (PGE) model to improve our understanding of shape-function relationships in engineering design. By decomposing system components into detailed shape sections and aligning them with specific variation shares, a method is presented that improves the ability to identify and quantify both similarities and differences in product designs. The granularity achieved through this method allows for more precise characterization of design variation, providing insight into the complex interplay between embodiment and function. However, it's important to note that the depth of analysis provided by this approach comes with an increased demand for detailed analysis and, consequently, a greater investment of effort and resources. Despite these challenges, the insights gained underscore the value of such detailed investigation, especially in applications where understanding subtle design nuances can lead to significant advances in product development and optimization.

Looking ahead, there are several promising opportunities to extend this research. One immediate area of interest is to explore the applicability of the method to a wider range of design challenges, particularly those involving complex structures where principal variations play a critical role. Understanding how these variations can be effectively segmented and analyzed using Functional Delimitation could open new pathways for innovation in design engineering. In addition, the potential for using this methodology to assess design risk and ensure product reliability represents an exciting frontier. By correlating

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variation shares with function criticality, designers and engineers could gain unprecedented insight into potential design vulnerabilities, enabling more informed decision making throughout the development process.

To conclude, this work provides the foundation for a new approach to engineering design that combines detailed analytical precision with strategic insight. By continuing to explore and refine these methodologies, the future holds the promise of not only more sophisticated design tools, but also a deeper understanding of the fundamental principles that govern the relationship between form and function. The journey ahead in advancing these concepts and applying them to diverse engineering challenges will undoubtedly contribute to the evolution of design theory and practice, pushing the boundaries of what is possible in product innovation and development.

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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