Implications of linking the C&C² approach and the model of PGE – Product Generation Engineering

Peter Michael Tröster, Tobias Dieck, Giorgi Tsutskiridze, Albert Albers

Karlsruhe Institute of Technology (KIT), Germany

Abstract: The integration of the C&C² approach with the PGE model aims to enhance knowledge capture, modeling, and analysis in product design. The C&C² approach, focusing on Embodiment Function Relations (EFR), aids in understanding the function of technical systems and supports developers during the design process. The PGE model manages knowledge from previous products to form new generations, categorizing variations that define new products. Combining these approaches, the research proposes a framework for detailed examination of Variation Shares within product components, improving accuracy in identifying differences and similarities between product variants. This contributes to knowledge retention and transfer in engineering, addressing demographic change and resultant knowledge outflow from companies. The paper highlights the implications of this combined approach for defining variation types and its potential to refine product development processes.

Keywords: Variation Shares, Embodiment Function Relations, Product Design, Variations Management

1 Introduction

At the heart of modern product development is an understanding of the embodiment function relations (EFR) that are essential to create innovative and efficient products. Understanding and describing these relationships is the basis for product design. Demographic change increases the urgency of this understanding as it leads to a significant outflow of information from companies as experienced engineers retire and take their implicit knowledge with them. This underscores the need to systematically capture knowledge about EFR and make it available for other engineers in product design. A proven approach to describe and model knowledge about EFR is the contact and channel approach (C&C² approach). The C&C² approach to model technical systems aims to support the thinking processes in the development process. It is to be understood as a meta-model which, according to the definition of Stachowiak, has model elements and basic rules (Stachowiak, 1973). It was developed specifically for modeling embodiment function relations (Matthiesen, 2021). In previous research, it was shown, that it is possible and beneficial to model into more detail, even within a single part (Tröster et al., 2024). This paper aims to explore the potentials and implications of combining the C&C² approach and the PGE model. By combining these approaches, a framework can be developed that enables knowledge about EFR to be captured, modeled, and analyzed into more detail. This leads to implications for the definition of various variation types, that will be discussed. The integration of both approaches promises to make a significant contribution to knowledge retention and transfer in engineering disciplines.

2 State of the art

As this paper refers strongly onto the Contact and Channel approach, it will be discussed first. Afterwards, the model of PGE – Product Generation Engineering will be introduced. The first attempts to combine both approaches will also be described in this chapter.

2.1 Modeling Embodiment Function Relations with the Contact & Channel Approach (C&C² approach)

There are various product models employed in embodiment design, each serving a distinct purpose. Examples of models incorporating graphical information about functions and embodiment include the Product Structure, He's Models, Gero's Models, Sketches and Symbolic Representations, SysML models, the Working Space Model, and the Contact & Channel Approach (C&C²-approach). (Matthiesen et al., 2019) In this work, the C&C² approach was chosen due to its ease of use and its wide applicability, which is crucial to be used for knowledge retention and transfer in engineering disciplines (Grauberger et al., 2022).

The C&C² approach is a method for graphical and descriptive modeling to support developers in the design process. Therefore, embodiment function relations (EFR) are modeled. There are three central elements to every C&C² model (see Figure 1):

- **Working Surface Pair (WSP):** These are surface elements created by the contact between two surfaces of solid bodies or the generalized interfaces of liquids, gases, or fields, engaging in the transfer of energy, materials, and/or information. (Matthiesen, 2021, 2002)

- **Channel and Support Structure (CSS):** These volume elements specify the space within solid bodies, liquids, gases, or areas penetrated by fields. They connect precisely two Working Surface Pairs, facilitating the movement of substances, energy, and/or information among them. (Matthiesen, 2021, 2002)
- **Connector (C):** Connectors merge effects that impact the system from outside the area of design, found within the subsystem represented using the C&C²-Approach. Featuring a representative Working Surface (WS), connectors act as a parameterized model for the pertinent external system environment. They are observed within the area of interest but lie outside the design space. (Albers and Wintergerst, 2014; Matthiesen, 2021)

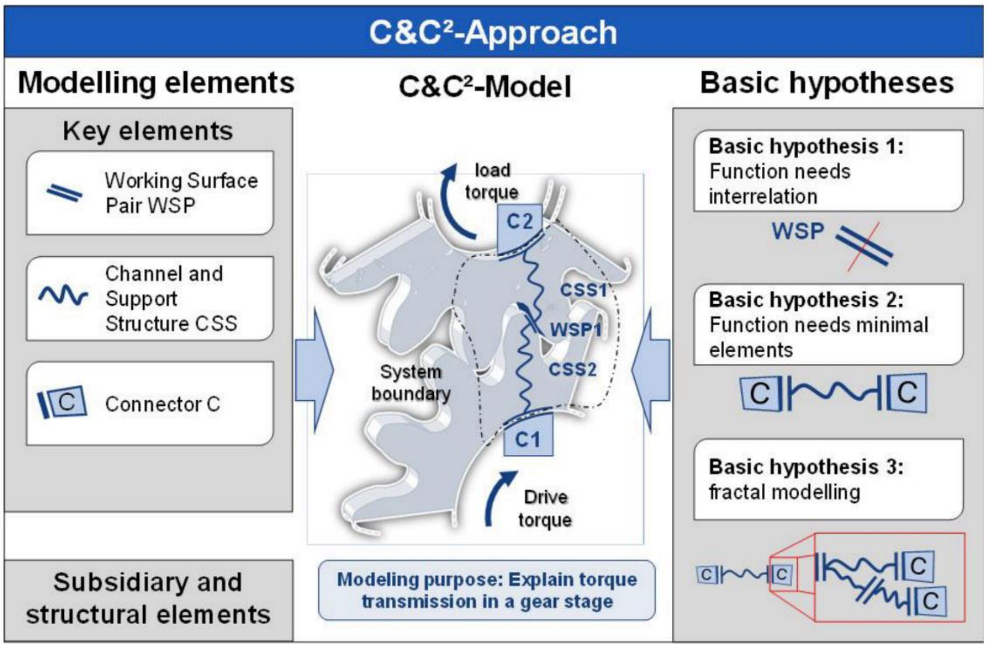

Figure 1: Elements of the C&C²-Approach according to (Matthiesen et al., 2018)

A new virtual model element of the C&C²-A is the so-called Functional Delimitation (FD) (see Figure 2). The Functional Delimitation is an analysis tool with which Channel and Support Structures (CSS) can be divided into segments without violating the basic hypotheses of the C&C² approach (Tröster et al., 2023). Along the path of a CSS, it can happen that it contains different functions or important changes in properties. In order to delineate and describe these functions, it is necessary to consider them in shape sections. There is no separation of the CSS into WSP. This would only be the case at an atomic level. The symbolic representation is based on two curved parallel lines The curved lines of the FD separate the CSS into areas between the connectors. The sections that are responsible for a specific characteristic therefore can now be specifically addressed and corresponding functions can be assigned. (Tröster et al., 2023).

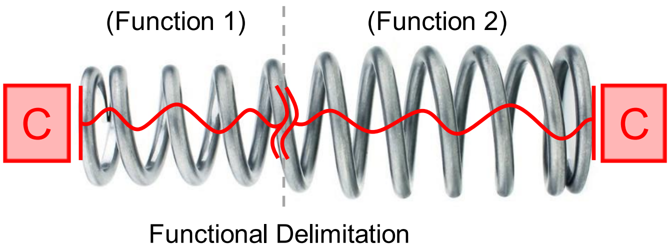

Figure 2: Functional delimitation in a screw spring (Tröster et al., 2023a)

2.2 The model of PGE – Product Generation Engineering

There are different approaches to describe product development. Those include the traditional design methodology, which differentiates between corrective and generative processes. Corrective processes involve minor changes to existing solution principles, while generative processes involve creating new solutions through abstraction and selection of new or recombined principles. Additionally, incremental innovation focuses on small improvements to existing systems, while radical innovation involves entirely new system structures. (Pahl et al 2007)

A more suitable model is the model of PGE – Product Generation Engineering because it provides a structured framework for developing new product generations based on existing reference products, which is more natural, as all products are based on references, consciously or unconsciously. This reduces technical and economic risks by allowing for both the adaptation of existing subsystems (Carryover Variations) and the creation of new ones (Principle Variations). PGE's iterative approach ensures continuous improvement and long-term market success, addressing the limitations of other methodologies which may not adequately balance innovation with risk management. (Albers et al., 2017)

The model of PGE – Product Generation Engineering, is part of the SGE – System Generation Engineering with a focus on technical products (Albers et al., 2022). It describes the development process of technical systems by defining in a formal way the types of variations that distinguish new products from their reference system. New product generations are often based on knowledge from previous reference products and reference system elements. Managing this information is critical to a successful development process, so PGE provides a structured understanding. The following types of variations can be used to describe new generations (Albers et al., 2015)

- **CV: Carryover Variation** (sometimes referred to as Adoption Variation) is accomplished by transferring subsystems, i.e., existing solutions from reference products or component suppliers, to the new product generations. Constructive adaptations should be minimized. (Albers et al., 2015)
- **PV: Principle Variation** describes the development of specific functional units using a new solution principle (compared to reference system). For this process, it is investigated, how the function can be fulfilled in other contexts. (Albers et al., 2015)
- **AV/EV: Attribute Variation (AV)/Embodiment Variation (EV)** is a new development of a subsystem through adjustments of the product embodiment, based on known (and established) solution principles. Embodiment Variation is the most common activity in product development and a highly creative and complex process. If there are variations of attributes, it is rather known as Attribute Variation. (Albers et al., 2015; Albers et al., 2023)

Principle Variation is crucial in product development as it drives innovation and the creation of new products by applying novel solution principles. However, Principle Variation also brings substantial risks, including technical challenges and the need for extensive validation and adaptation measures. These risks exist due to a lack of knowledge about the novel solution principles, therefore, gaining a better understanding for novel solution principles is crucial. (Albers et al., 2017)

In addition to the categorization of variation types for the development of new product generations, the PGE model is also used for other aspects of product development. These include, for example, the modeling and managing of product portfolios. (Schlegel et al., 2023)

2.3 Combination of the C&C² Approach and the PGE Model

Combining the C&C² approach with the PGE model allows for a more nuanced analysis of Variation Shares within product components, increasing the accuracy with which differences and similarities between product variants can be identified and evaluated. By applying the Functional Delineation of the C&C² approach alongside the structured variation categorization provided by the PGE model, engineering can break down complex components into manageable sections. This methodical segmentation allows a detailed assessment of how each part contributes to the overall function and design evolution of a product. (Tröster et al., 2024)

The process of determining Variation Shares starts with Functional Delimitation. This initial phase identifies the component's functional elements, such as Work-Surface-Pairs (WSP), Channel-Support-Structures (CSS), and Connectors, essential for understanding its functional interactions.

Next, Segmentation breaks the component into manageable sections based on Functional Delimitation, isolating variations for focused analysis. The application of the PGE model then categorizes these variations into Carryover Variation (CV), Principle Variation (PV), and Embodiment Variation (EV).

At last, Variation Shares are derived. There are several possibilities to quantify the Variation Shares. By number of sections, length, area or volume. (Tröster et al., 2024)

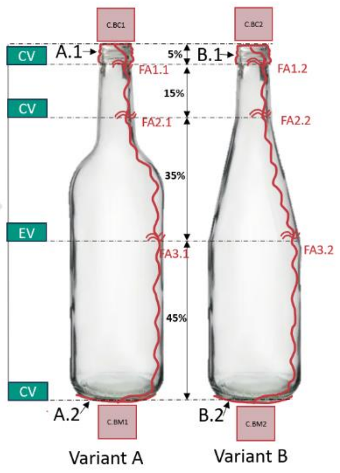

Figure 3: Modeling the types of variation using the example of two bottles by Function Delimitation (Tröster et al., 2024)

3 Methodology

Based on the desire to develop a procedure for the improved utilization of product-specific knowledge, the idea for a detailed breakdown of the proportions came into being. In order to make the knowledge gained via the C&C² approach usable, the variation proportions between the development generations and product generations were to be visualized on the shape. In this way, product-specific knowledge can be made explicitly visible, thus additionally increasing the information content. This raised multiple questions about a more precise procedure for delimiting, subdividing and determining the variation proportions in connection with the C&C²-A. Therefore, the research questions are:

- How does the combined use of the C&C² approach and the PGE model facilitate the systematic capture and transfer of engineering knowledge, especially in the context of demographic changes and knowledge outflow?
- Is Principle Variation composed of Attribute Variation and Carryover Variation components, and how can these components be identified and categorized?
- How does the integration of the C&C² and PGE models facilitate the retention and transfer of engineering knowledge, particularly in the context of demographic changes and the outflow of experienced engineers?

To answer these questions, this work is grounded in a qualitative research paradigm, leveraging the extensive experience of the authors in the fields of engineering design and product development. The study is characterized by an iterative process development, where the combined use of the C&C² approach and the PGE model was refined through repeated cycles of application, observation, and modification.

In the end, a case study on the generation engineering on the example of a monotube shock absorber to a twin-tube shock absorber was conducted.

4 Results

In previously published research, it was shown that it is worthwhile to determine Variation Shares on individual system components section by section (Tröster et al., 2024). The detailed subdivision increases the effort, but also the information content about the Variation Shares. The proportions can be determined in different ways. 1) Counting the sections, 2) determining the area, 3) the volume or 4) relating the shape section to the total length of the shape section.

In conjunction with the Functional Delimitation (FD), the criticality of the variation sections and the functions present there can also be better assessed. With the help of the example of bottle variants A and B from the (Tröster et al., 2024) paper, initial examples were provided of how the proportions of Carryover Variation (CV) and Attribute Variation (AV) are composed on a system component (see Figure 3).

4.1 Proposed approach to derive Variation Shares of components

However, the Principle Variation (PV) has not yet been considered in more detail. The question therefore arises as to how the Principle Variation behaves when determining the proportions section by section and how the analysis using the C&C²-A can support this. There is currently no fixed procedure for determining Principle Variation components.

As components, we define in this research: “A component is an individually identifiable element that may be incorporated into a larger mechanical, electrical or electronic system that cannot be further separated from its intended initial state.”

Initial investigations into how a Principle Variation manifests itself in conjunction with the C&C²-A were carried out in the scientific contribution to the investigation of a dual-mass flywheel (Albers et al., 2017). In this study, a Principle Variation was always accompanied by a change in the number of pairs of Working Surfaces and Channel and Support Structures (CSS).

But how can a PV be determined in general?

To this end, it is important to first consider when a Principle Variation can exist at all. First, we must acknowledge, what the variations refer to. It is in general the generation of the product, that is in the market. Whether the current generation in development is a Principle Variation can only be considered in relation to previous generations like the one in the market G_{n-1}. Recent research proposed that the addition and removal of pairs of Working Surfaces is always accompanied by a variation in principle and thus a change in the operating principle and solution principle (Albers et al., 2017). We propose, that this cannot simply be applied universally. Working principles and solution principles are often partly adopted from the previous generation or new principles are adopted from reference system elements that are not part of the product.

First of all, we need to clarify the definition of Principle Variation. We propose the following definition:

“A Principle Variation represents a fundamental shift in a product's design or functional principle, integrating changes across attribute and carryover components to realize a new, distinct operational concept compared to its previous generation.”

Operating principles or solution principles often only become possible when different components interact and together form the resulting principle. The individual components often form an assembly. Within an assembly, however, there are many components that can be adopted unchanged or only need to be adapted slightly so that they can be integrated into the

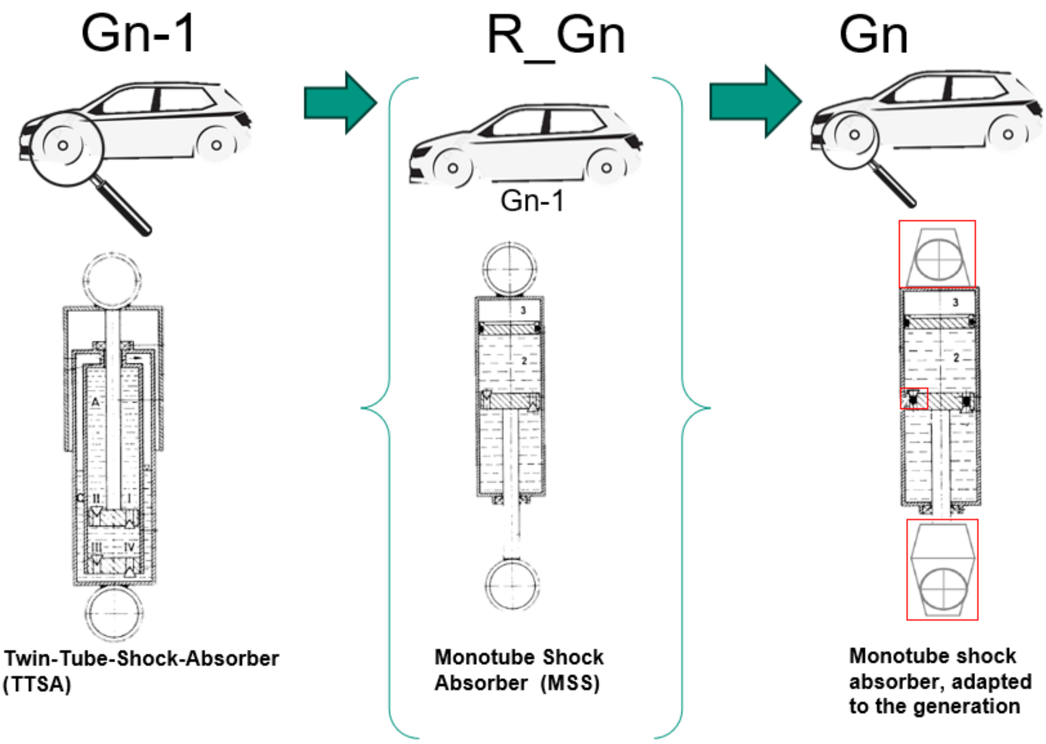

Figure 4: Generation engineering on the example of a monotube shock absorber to a twin-tube shock absorber

G_n to be developed. An example is the generation engineering from a monotube shock absorber to a twin-tube shock absorber (see Figure 4). This change represents a significant change in principle for the G_n, as the functional principle between the shock absorber variants differs at key points, such as the gas bladder in the monotube shock absorber. The number of components required to fulfill the function also differs.

This raises the question of whether the Principle Variation is not also made up of the Attribute Variation and Carryover Variation components. These individual components, which together represent the principle, are therefore part of the Principle Variation. In addition, the composition of a Principle Variation and the associated risk of the Principle Variation can be estimated and evaluated more accurately if its composition can be broken down into Attribute Variation and Carryover Variation components. In this sense, the Principle Variation includes all components that are necessary to fulfill the solution or operating principle.

A finer division of the Variation Shares would therefore make sense

A suggestion for a finer subdivision of the Variation Shares is shown below. In addition to the Principle Variation, which can consist of the Attribute Variation and Carryover Variation, the Carryover Variation is further subdivided into an adapted share and an unchanged share. This step is necessary so that a clear distinction can be made between unchanged and slightly adjusted portions that are not yet part of the Attribute Variation.

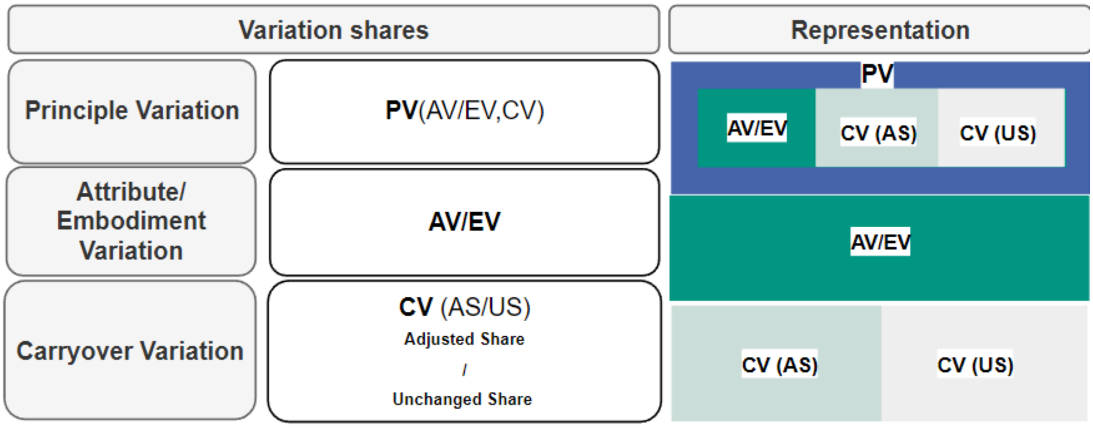

Figure 5: Overview of different types of variation and proposed more detailed subdivision

A proposal for determining the subdivided Variation Shares of Principle Variation

To determine the subdivided Variation Shares of Principle Variation, we propose the following procedure (see Figure 6):

To streamline the process described, we can organize it into a more structured and comprehensible approach while retaining the technical terminology. Here's a simplified, step-by-step structure:

- **Classify the Reference System Element:**
  Begin by considering the reference system element as a whole, regardless of whether it's composed of multiple components forming an assembly. This holistic view ensures all parts are evaluated in their contribution to the overall function (Tröster et al., 2024).
- Assess **Principle Variation**:
  - **Evaluate Changes in Operating or Solution Principles**:
    Compare the current system (G_n) against the previous generation (G_{n-1}) to identify any changes in operating principles or solution principles. This involves examining energy, material, and information flows to see if new physical or chemical properties and quantities are employed to achieve the desired function.
  - **Examine Component and Working Surface Changes**:
    Determine if the number of components and Working Surfaces used to achieve the desired function has changed, indicating a different effective structure from G_{n-1}.
- **Determine Variation Proportions**:
  - **Section-by-Section Analysis**:
    Once a Principle Variation is identified, analyze the variation proportions of the individual component parts. This detailed examination helps in understanding how each part contributes to the overall change.
  - **Inspect Changes in Working Surfaces**:
    Check whether a change in the number of Working Surface Pairs or their arrangement is necessary for integration into G_n. Any change in the volume shape or the arrangement of Working Surface Pairs suggests a shape variation.
  - **Identify Type of Variation**:
    If there are no changes in the number of Working Surfaces, assess if there's a change in their arrangement

or the shape of the volume. This could also result in a shape variation. If no changes are observed, consider it a Carryover Variation. Further, evaluate if the Working Surfaces or boundary surfaces have been modified (e.g., in roughness, hardness) without volume changes, classifying it as an adjusted Carryover Variation.

- **Outline Principle Variation Components**:
  Finally, outline the component parts that collectively represent the operating principle or solution principle identified as a Principle Variation. This step clarifies how each component's modification or inclusion contributes to the new principle.

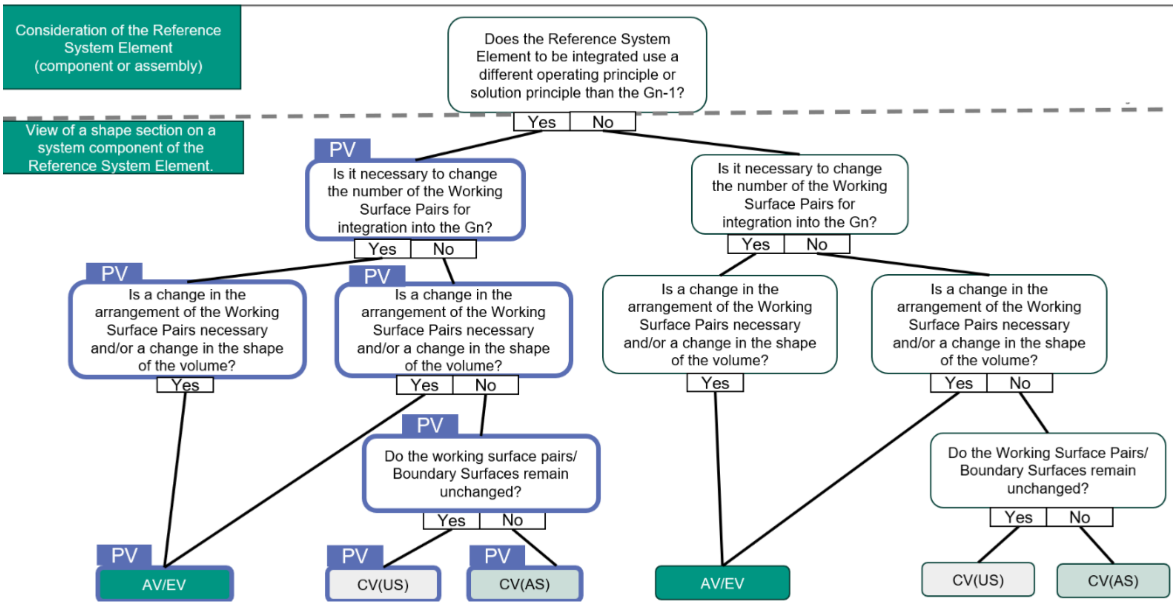

Figure 6: Process to distinguish the variation type on basis of C&C² models

To validate the proposed process, a study on the generation engineering of a monotube shock absorber to a twin-tube shock absorber was conducted (see Figure 7). The components have been highlighted with corresponding colors (see Figure 5). All components of the assembly are outlined by the Principle Variation, as they represent the solution principle in their interaction. The individual components that make up the damper were largely taken over unchanged from the Reference System Element of the monotube shock absorber and therefore represent a Carryover Variation part within the Principle Variation. However, the effective areas and therefore the volumes of the valve plates were changed, as was the damper's suspension. For this reason, Attribute Variation components must be assigned within the Principle Variation.

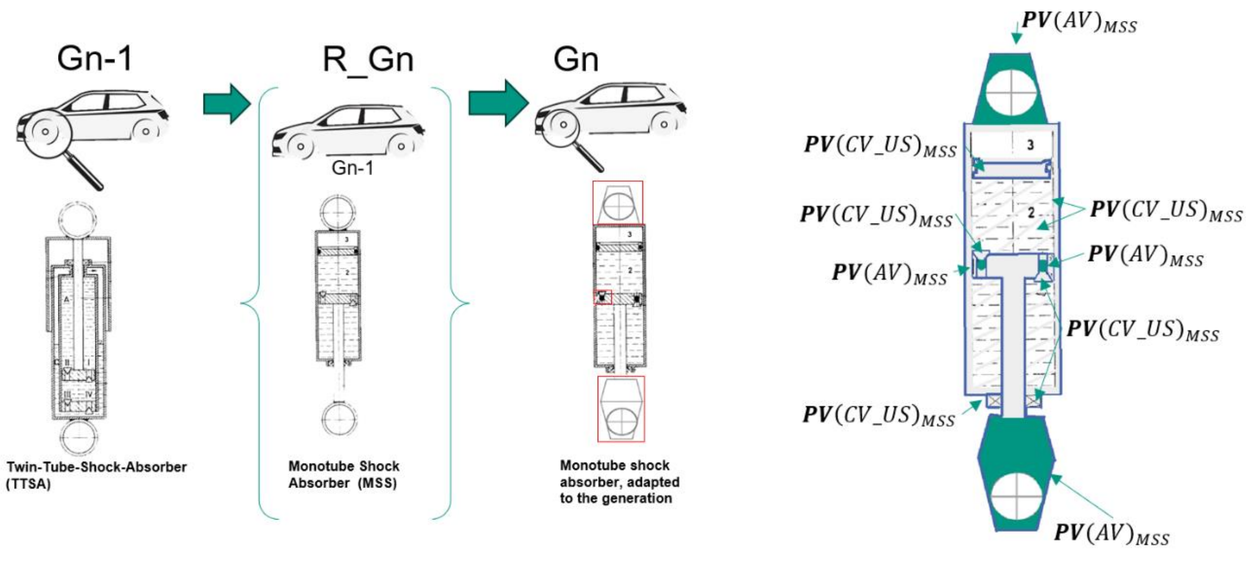

Figure 7: Subdivided Variation Shares of a Principle Variation on the example of generation engineering of a monotube shock absorber to a twin-tube shock absorber

5 Discussion

The linking of the C&C² approach with the PGE model – Product Generation Engineering presents a novel framework for enhancing product design through improved knowledge capture, modeling, and analysis. This synergy not only facilitates a deeper understanding of Embodiment Function Relations (EFR) but also leverages knowledge from prior product generations to improve the development of new ones. The combined approach is meant to improve the precision in identifying and categorizing variations, thereby enhancing innovation and design efficiency.

The presented combined approach of C&C² modeling and the variation types of the model of PGE promises advantages for the management of changes in the development process. The detailed breakdown of Variation Shares into Principle, Carryover, and Attribute Variation increases the transparency of EFR and how they are influenced by changes. This can be used as a basis for argumentation when making decisions about changes. The modeling of functional boundaries with the help of Functional Delimitation also allows the identification of critical functional areas that should be given special attention when making changes. Therefore, the combined approach promises improved change management through increased transparency of variation and functional relationships.

By breaking down the Principle Variation (PV) into the parts of Attribute Variation (AV) and Carryover Variation (CV), it is easier to characterize Reference System Elements that are present as an assembly consisting of many individual components. By initially looking at several components that represent the operating and solution principle at hand, it can be decided more clearly whether the G_n currently under development is a Principle Variation and which components are involved. The elements of the C&C²-A, such as the Working Surface Pairs or already known energy, information or material flows, can also be included in the assessment. The more precise division of the Carryover Variation (CV) into an adapted and an unchanged part helps to record important design differences in system components that are not directly recognizable from the outside. This results in a clearer possibility to record Variation Shares between the development and product generations.

6 Summary

This paper presents a framework that links the C&C² approach with the PGE model, aiming to support product design through improved knowledge capture, modeling, and analysis. By focusing on Embodiment Function Relations (EFR) and leveraging knowledge from past product generations, this approach facilitates a detailed examination of Variation Shares within product components. This not only enhances the accuracy in identifying design variations but also significantly contributes to knowledge retention and transfer in engineering disciplines. Therefore, it provides guidance on how the Reference System Elements used in a product generation can be broken down into the aforementioned components of PV, AV/EV and CV. For this purpose, a different division of the Variation Shares was made, in that the Principle Variation itself is made up of the shares of the Carryover Variation and Attribute Variation. So that even slight design changes to the shape can be differentiated more precisely, the Carryover Variation was also divided into an adapted and unchanged portion. In addition to the subdivision of the Variation Shares, important information was provided on how a principle variation can be recognized.

7 Outlook

In future studies, in conjunction with a C&C² analysis and the corresponding C&C² model, the Variation Shares should be examined in more detail and more precisely on more complex assemblies and systems. This should also include a precise recording of the percentages of the Variation Shares by design section, as already mentioned in recent research (Tröster et al., 2024). In this context, it would be interesting to take a closer look at the criticality of the Principle Variation for the generation to be developed, which is possible in more detail by breaking it down more precisely into Attribute and Carryover Variation. The application of Functional Delimitation can also be used here for a more precise functional delineation of individual shape sections within the C&C² analysis.

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References

Albers, A., Bursac, N., Rapp, S., 2017. PGE – Produktgenerationsentwicklung am Beispiel des Zweimassenschwungrads. Forschung im Ingenieurwesen 81, 13–31. https://doi.org/10.1007/s10010-016-0210-0.

Albers, A., Bursac, N., Wintergerst, E. Product Generation Development - Importance and Challenges from a Design Research Perspective: Proceedings of the International Conference on Mechanical Engineering (ME 2015), Vienna, Austria, March 15-17, 2015 : proceedings of the International Conference on Theoretical Mechanics and Applied Mechanics (TMAM 2015) Vienna, Austria, March, 15-17, 2015, in: New Developments in Mechanics and Mechanical Engineering, vol. 13, pp. 16–21.

Albers, A., Hünemeyer, S., Kubin, A., Pfaff, F., Schlegel, M., Rapp, S., 2023. Modelling Technical Systems in the Early Phase: Proposing a Formal Definition for the System Concept. Proc. Des. Soc. 3, 2695–2704. https://doi.org/10.1017/pds.2023.270.

Albers, A., Kürten, C., Rapp, S., Birk, C., Hünemeyer, S., Kempf, C., 2022. SGE – Systemgenerationsentwicklung : Analyse und Zusammenhänge von Entwicklungspfaden in der Produktentstehung. Karlsruher Institut für Technologie, 19 pp.

Albers, A., Wintergerst, E., 2014. The Contact and Channel Approach (C&C2-A): Relating a System's Physical Structure to Its Functionality, in: Chakrabarti, A., Blessing, L.T.M. (Eds.), An Anthology of Theories and Models of Design. Springer London, London, pp. 151–171.

Grauberger, P., Bremer, F., Pfaff, F., Tröster, P., Nelius, T., Eisenmann, M., Stöberl, T., Albers, A., Matthiesen, S., 2022. Gaining insights through qualitative modelling - industrial project analysis with focus on derived hypotheses based on the contact and channel approach. Procedia CIRP 109, 478–483.

Matthiesen, S. Gestaltung - Prozess und Methoden, in: Pahl/Beitz Konstruktionslehre, vol. 9, pp. 397–465.

Matthiesen, S., 2002. Ein Beitrag zur Basisdefinition des Elementmodells "Wirkflächenpaare & Leitstützstrukturen" zum Zusammenhang von Funktion und Gestalt technischer Systeme. 1615-8113 6. https://doi.org/10.5445/IR/12092002.

Matthiesen, S., 2021. Gestaltung – Prozess und Methoden, in: Bender, B., Gericke, K. (Eds.), Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 397–465.

Matthiesen, S., Grauberger, P., Hölz, K., Nelius, T., Bremer, F., Wettstein, A., Gessinger, A., Pflegler, B., Nowoseltschenko, K., Voß, K., 2018. Modellbildung mit dem C&C²-Ansatz in der Gestaltung: Techniken zur Analyse und Synthese. KIT Scientific Working Papers ; 58.

Matthiesen, S., Grauberger, P., Bremer, F., Nowoseltschenko, K., 2019. Product Models Embodiment Design - an Investigation of Challenges and Possibilities.

Pahl G, Beitz W, Feldhusen J, Grote K-H, 2007. Pahl/Beitz Konstruktionslehre: Grundlagen erfolgreicher Produktentwicklung. Methoden und Anwendung. Springer, Heidelberg

Schlegel, M., Wiederkehr, I., Rapp, S., Koldewey, C., Albers, A., Dumitrescu, R., 2023. Design of a Descriptive Model for Product Portfolio Evolution Based on the Model of SGE – System Generation Engineering. R&D Management Conference, Seville Spain, Responsible and Responsive Innovation for a Better Future.

Stachowiak, H., 1973. Allgemeine Modelltheorie. Springer Wien.

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. Stuttgarter Symposium für Produktentwicklung, Stuttgart. 25.05.2023, pp. 175–186.

Tröster, P.M., Tsutskiridze, G., Dieck, T., Albers, A., 2024. A new Approach to derive Variation Shares by Combining the C&C² Approach and the PGE Model. DESIGN2024.

Contact: Peter Michael Tröster, Karlsruhe Institute of Technology (KIT), IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany, +49 721 608 47252, +49 721 608 46051, peter.troester@kit.edu, https://www.ipek.kit.edu/21_8246.php