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A Designation Guide for Consistent Cross-System-Level Modeling of Embodiment Function Relations

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Abstract

In the early phase of product development, the possibility of goal-oriented discussion of complex systems is particularly important to avoid communication errors. In practice, misunderstandings occur repeatedly when discussing systems, since different contents are verbalized unconsciously. To address this problem, systems to be analyzed can be divided into subsystems and system elements can be considered. This problem can also be addressed by using approaches for the consideration of system elements and of embodiment function relationships (EFR). One of these approaches is the so-called C&C² approach. Although this approach has been used successfully many times, its practical applications have so far shown differences in the designation of the elements. As a result, systems and models cannot always be compared with each other with sufficient accuracy. A further point is the constant change of the systems during the product engineering process (PEP), which up to now can hardly be consistently represented in the designations of the model elements. For this reason, a designation guideline was developed for the C&C² approach, which enables the consistent designation of systems and model elements throughout the entire PEP. In addition, the approach consistently allows for any level of detail across the entire PEP. This designation guide has been validated very successfully in a case study in automotive engineering. In the future, the designation guide will allow many models to be compared, thus enabling the creation of a database. This can be a cornerstone for development with artificial intelligence in the future.

Keywords: product engineering; product development; product design; design methodology; embodiment function relations; collaborative design

1. Motivation

During product development processes, highly complex systems are usually considered. These often interact with each other and thus influence each other. To handle this complexity, various approaches exist that are intended to increase the understanding of the system. Those approaches are used to model embodiment function relations (EFR). In product development, documenting EFR is crucial for several reasons. Firstly, with the increasing shortage of skilled labor, it is essential to ensure that knowledge is not lost as personnel changes occur. Having clear and comprehensive documentation of embodiment function relations ensures that new team members can quickly get up to speed and continue to work seamlessly. This can save time and resources, as well as prevent mistakes and misunderstandings. Secondly, having detailed documentation also enables easier maintenance and updates to the product, making it easier to address any issues that arise in the future. Finally, clearly understanding the embodiment function relations can lead to improved design and functionality, as well as a better user experience. To be able to achieve a detailed documentation of EFR, it is necessary to have a consistent designation guide.

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2. State of the art

2.1. Product models for embodiment design

There are multiple product models that are used in embodiment design, each with a different purpose (see Fig. 1). Models that feature graphical information about functions and embodiment are for example the Product Structure [1], Models according to He [3–5], Models based on Gero [6], Sketches and Symbolic Representations [7], SysML models [8], the Working Space Model [9] and the Contact & Channel Approach (C&C²-approach) [10, 11]. [12]

A commonly used approach for the modelling of embodiment function relations (EFR) is the so-called Contact and Channel Approach (C&C² approach) [13]. It supports product developers to obtain insights by using the core elements Working Surface Pairs, Channel and Support Structures and Connectors (see Fig. 2). **Working Surface Pairs (WSP)** are created when two arbitrary shaped solid body surfaces or generalized interfaces of liquids, gases, or fields come into contact and exchange energy, substances, and/or information. **Channel and Support Structures (CSS)** are components of volume. They refer to volumes of solids, liquids, gases, or field-permeable spaces that connect precisely two pairs of working surface pairs and permit the transmission of material, energy, or information between them. **Connectors (C)** are an abstraction of the system environment that integrates the relevant properties lying outside the system boundary into the system analysis. They have a representative working surface and an associated model of the relevant system environment and are located in the area of consideration, but not in the design space. Three hypotheses are important for the modeling. Frist, functions need interaction. This is why the C&C² approach analyzed the pairs of working surfaces. Second, function needs a minimal number of core elements. And for this paper most important, the fractal modeling. If a model does not explain a problem, it is always possible to model in more detail. [2]

These core elements help to better understand the systems under consideration and to be able to analyze them in a targeted manner. This is due to the link of the product functions with its physical structure [14] and thus a better understand of their interaction with each other [2].

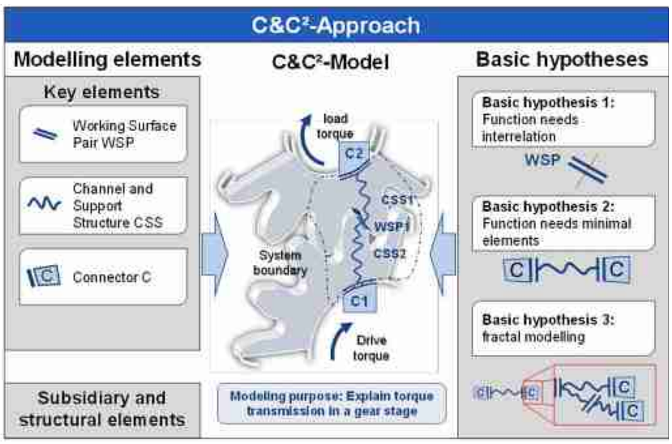

Fig. 2: Elements of the C&C²-Approach according to [2]

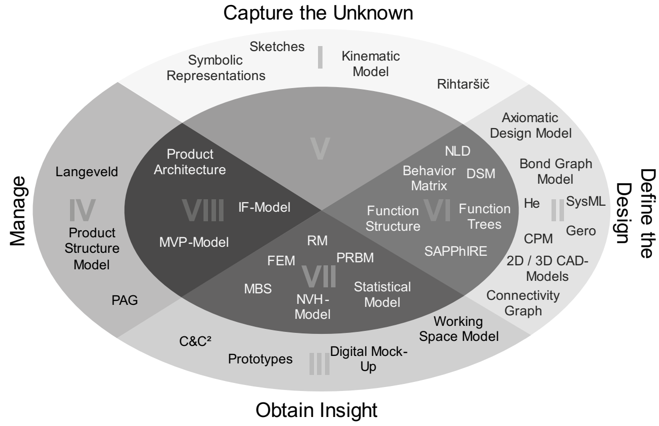

Fig. 1: Different categories of product models based on their purpose according to [1]

2.2. Different approaches for element designation

There are multiple types of designation of the individual elements of the C&C² approach (WSP, CSS, C), due to a lack of a specific designation guide. Consequently, the designation of elements is dependent on the perspective of the individual using the methodology. This complexity arises when the system under examination contains elements from multiple domains, such as mechanical and electrical. The lack of standardization in element categorization results in a lack of consistency in discussion and impedes the full utilization of the methodology. If the C&C² elements are designated differently in different domains, there is no uniform basis for discussion and the full potential of the approach is not exploited. Furthermore, the non-uniform designation of components makes it challenging to maintain consistency in element naming throughout the product development process. The designation of the elements has so far been carried out differently depending on the user of the approach (see Fig. 3):

2.2.1. Sequential numbering of C&C² elements:

The components are systematically numbered sequentially, proceeding either from left to right, or from top to bottom, or vice versa. This methodology is frequently employed during the manual creation of models, such as WSP1, WSP2, and WSP3. [10]

2.2.2. Designation of WSP depending on the labels of C and CSS:

The designation of the WSP elements is determined based on the previously established naming convention for the connectors and the CSS. For instance, in the case where the Channel and Support Structure "CSS 3.1" connects the connectors "C1" and "C2" through WSP, the first WSP is referred to as "C1 - CSS 3.1" and the second WSP as "CSS 3.1 - C2". The order in which the components are named within the designation of the respective WSP is noteworthy. If the connector is located on the left-hand side, it is named first, followed by the CSS. On the other hand, if the connector is located on the right-hand side, the CSS is named first, followed by the connector. However, this naming convention does not reflect the direction of the forces acting on the connectors in

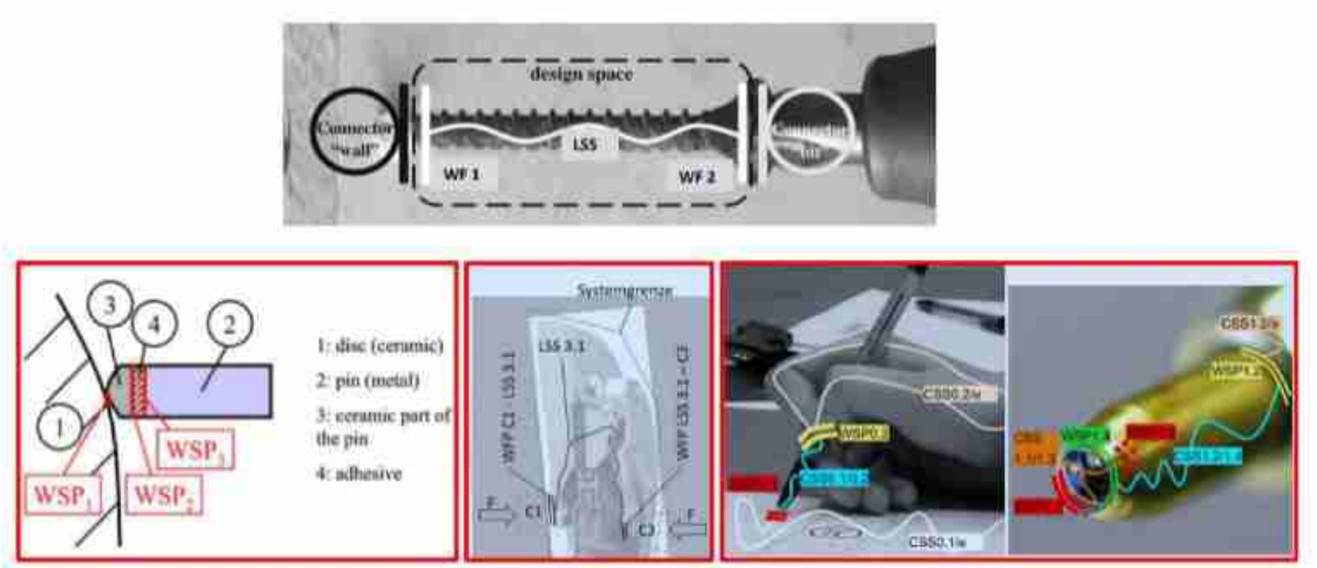

Fig. 3: Different approaches for the designation of C&C approach elements in models. [11, 15, 17]

the direction of the inner CSS. It is based on a left-to-right order according to the first element present. It must be noted that this designation methodology is only applicable to the current two-dimensional representation of the system and is not suitable for rotation as it would compromise the logical consistency of the designation. [15]

2.2.3. WSP as a function of the time (A1, B2, ...)

It is possible to categorize the WSP elements based on their point of utilization in time. For example, during the screwing process of a screw, there is a WSP located at the tip of the screw, which serves the purpose of cutting the material. Other WSP are generated after the screw has penetrated the material. For instance, the cutting WSP may be designated with the suffix "A1" and the WSP created during the penetration process may be designated with the suffix "B2." This distinction allows for the optimization of each individual state, as it becomes clear which WSP, CSS, and functions are in operation. In this scenario, WSP A1 only requires optimization for a specific subset of states, while WSP B2 must be optimized for the entire screwing process. [16]

2.2.4. WSP by main and partial function (1.x)

The components of a system, which play a significant role in fulfilling the main function, can be designated using the number "1" when the system is viewed at a particular level of detail. If the level of detail is increased, the elements of the higher level of detail can be designated as "1.x". This clearly indicates the main function that these elements contribute to and their respective sub-functions. Additionally, the WSP elements can be named according to the respective subsystem and consecutively numbered within the subsystem. For example, if a pen held in the hand is considered, the outermost subsystem "0" is composed of the writing hand and the pen. The WSP elements of this subsystem are denoted as "0.x", where "x" is a consecutive number of the WSP elements within the system. The CSS elements are denoted by the respective WSP elements they connect and separated by a slash. For instance, the "CSS0.1/0.2" connects the "WSP0.1" to the "WSP0.2". Another subsystem is the pen itself, which is referred to as subsystem "1", and its components are referred to as "1.x" following the previously described method. Instead of using connectors at the system boundaries, CSS elements are defined, which serve as a second WSP that represents the external environment behind the partial system boundary. [15, 17]

3. Methodology, research gap and research questions

The study conducted for this paper includes the analysis of C&C²-approach literature and literature of designation systems. The goal was to get a basic understanding of how C&C² models can be designated and recognize the main ideas, theories, and techniques involved. To identify designation systems in C&C² models, only peer-reviewed literature containing models were analyzed. To widen the view, and to derive key concepts, general literature about designation systems was analyzed.

The analysis of the literature of C&C² and designation systems revealed that there is a variety of approaches to designate elements of C&C² models. The aim of this research is to develop a guideline for the uniform designation of C&C² elements. Based on a development project in the automotive company, a new designation guideline for C&C² elements was developed and applied in the same development environment.

The research conducted as part of this project will answer the following research questions:

- RQ1: What standards should a designation guideline for embodiment function relations meet?
- RQ2: How is it possible to designate the C&C² elements uniformly?
- RQ3: How can information regarding element positioning and temporal element action be integrated within a C&C² element name as a function of element functions?
- RQ4: How must the designation guide for C&C² elements be structured to support the memorization process of C&C² element designations?

- RQ5: How can the designation be adapted to suit the problem?

4. Results

Based on the literature review and additional interviews with participants of the development project as well as experts on the C&C² approach, the following six requirements for designation guidelines were identified (see. Table 1)

Table 1: Requirements for designation guidelines

Identified requirements	Description
Unambiguity	Designations must be unambiguous so that everyone understands and uses them unambiguously.
Comprehensibility	The designations should be understandable for the target group and not have any unnecessary complexity.
Consistency	Designations should be used consistently within the system and over time to avoid confusion.
Relevance	Designations must be relevant to the system or project and consider the needs of the target audience.
Flexibility	Designations must be flexible to adapt to future changes and to match the purpose of the modelling.
Documentation	The naming convention must be well documented to ensure that it is used correctly.

To designate C&C² elements uniformly, a designation guide was developed to match the identified requirements. It is based on previous used approaches for designation analyzed in the literature review. The designation guide is divided into 5 steps, which are presented and explained below using the designation of WSP (see Fig. 4).

4.1. Step 1 – Definition of systems

In the first step, the overall system at hand, consisting for example of one or more individual parts, is divided into main systems (MS). These systems are differentiated from each other in that they fulfill different functions. Consequently, several MS can also be present within a single individual component. The systems are designated by letters, whereby these can provide information about the system if required.

Consequently, the front of the car can be designated as system "F". If further specification is required, the front could be subdivided into subareas like the center, e.g., ("FC"), whereby this in turn forms an independent system.

4.2. Step 2 – Definition of subsystems

The subsystems (SS) identified in the second step concretize the previously identified systems. SS are marked with numbers, which can be defined consecutively. If the SS "1" is to be further concretized, another number is added which is connected to the first number by a dot, for example a SS can be called "1.1". Together with the system identified in the first step, this consequently results in a considered subarea of the system, e.g., "F1.1".

4.3. Step 3 – Designation of CSS and WSP

The previously defined system subarea can form an effective area, a Working Surface (WS) that interacts with other WSs, thus forming a WSP. Two interconnected WSs are connected by slashes "//". These slashes follow the character of the double bar used in all literature sources to indicate a WSP (see Table 2). For CSS, a tilde is used, as it represents the swings of CSS.

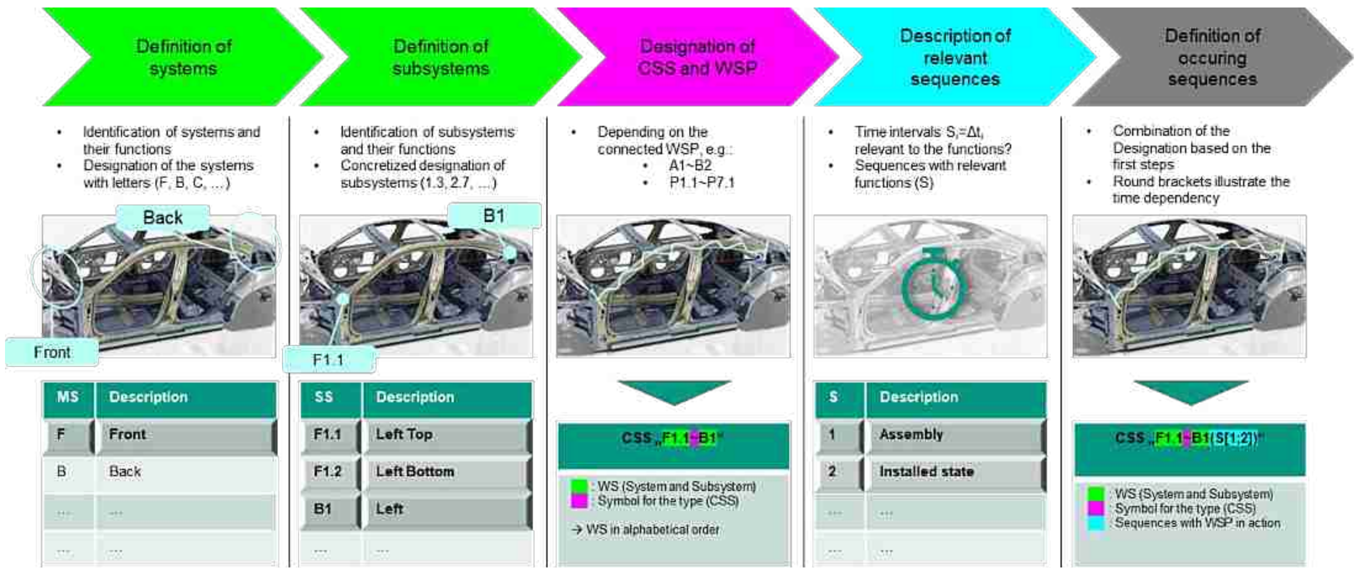

Fig. 4: Procedure for the designation of CSS with the help of the new designation guide for C&C² elements. Image [18]

Table 2: Symbols of the designation guide for modelling with C&C² approach

Designation element	Symbol	Explanation
Double slash	//	Identification of WSP formed by contact of individual WS.
Tilde	~	Identification of CSS that form between individual WSP.
Semicolon	;	Separation of individual effect sequences-

4.4. Step 4 – Description of relevant sequences

Since WSP can fulfill different functions for different effect sequences, the sequential effect is determined for each WSP derived from MS and SS. This results from the times in which the WSP fulfills a new effect function compared to the previous effect sequence. The effect sequences are concretized in tables, and "(…)" is appended to the WSP designation in round brackets. If several effect sequences are present, they are indicated in square brackets as effect sequence set and separated from each other by a semicolon. The letter "S" indicates a sequence.

4.5. Step 5 – Definition of occurring sequences

If the previously determined subsystem "BD1.1" forms an effective area with the SS "BD2.4", which acts to sequences during production (effective sequence "1") and in an installation state (effective sequence "6"), the following designation for the WSP follows in summary: "BD1.1//BD2.4(S[1; 6])". The MS designations are always given in alphabetical order.

The designation of the CSS follows the same scheme, using a tilde (~) instead of the two double dashes to separate the MS and SS. This corresponds to the curved line used in principle in the literature to imply to be a CSS.

5. Discussion

Through a first literature review and interviews with experts, a first overview was given and requirements for designation guidelines could be derived. These requirements provide a first overview, but must be further analyzed and backed with more studies in the future. By matching the requirements to the identified designation systems used in previous C&C² models, it is clear, that they do not fulfill the identified requirements. Most of all, there was no documented designation guideline found. The designation based on sequential numbering for example lacks the requirements of being flexible. If new elements need to be added and designated, the labeling will have higher numbers next to lower numbers or all elements would need a re-labeling.

The proposed designation guide for C&C² elements is designed to match the requirements. At first, it is documented in a guideline, that provides an example. Second, the designations aim to be comprehensible and unambiguous due to their structure of unique letters and numbers. The use of letters to define the main system (MS) allows for better memorization of the MS. This is because psychological studies have shown that by using letters, users can memorize and remember them better and recall this knowledge even after several months. [19] Since the MS are concretized by subsystems (SS) with letters, a visual link is created between the SS and the number combination. This designation of the SS linked with a visualization increases the memorability of the SS [20]. Subconsciously, the designation logic for the MS and SS uses the human brain in a target-oriented manner to ensure the best possible memorization of the system areas under consideration.

To be flexible, the designation guide provides the possibility to increase the level of detail by adding new numbers. Fractality is also a key aspect of the C&C² approach. The designation guide enables therefore an adaptation of the observation level, since both overall systems and microscopically small observation and analysis areas can be designated uniformly. This can support the cross-domain use of the designation guide, since different development areas can designate the product in consideration relevant to them, and these selected designations can be adopted and adapted by the adjacent area of consideration.

Moreover, it is possible to describe the logic state S by adding it after the rest of the designation (e.g., xxx(S[1; 3]). This allows to set multiple states. Furthermore, it is possible to describe specific times. This can be useful by analyzing footage of high-speed cameras. To accomplish this, it is possible to replace the numbers through the expression, for example. (t = 0.03s). The round brackets within the designation guide indicating the effect sequences of the Working Surface Pairs (WSP) can increase the understanding of the designation guide. This is because round brackets imply temporal dependence. If there is no need for adding logic stats, they can be left out. This adds to the flexibility of the designation guide. Moreover, it allows adjusting the designation based on the individual needs, but follows a given rule.

Since in many system considerations only individual components must be considered, it is possible to start with a designation of the Channel and Support Structures (CSS). In numerous instances, this will be sufficient, since WSP only become relevant when several adjacent systems are considered, and thus the modeling effort can be kept as small as necessary.

6. Outlook

Further research and case studies are necessary to better understand how functions within a single Channel and Support Structures (CSS) and within a single component can be distinguished from one another. Even when only a single component is considered in many applications, it may still fulfill different and multiple functions. This is especially important for 3D-printed parts.

In addition, further studies should focus on applying and validating the applicability of the designation guide across different domains. This will help to establish its effectiveness and usefulness, and potentially lead to its widespread adoption.

The future holds great potential for the designation guide, as it will allow for the comparison of many models and the creation of a database. This database can serve as a cornerstone for development with artificial intelligence, providing a foundation for more advanced and intelligent product design.

In conclusion, the future of product development holds exciting possibilities, and further research and study into the designation guide and its potential applications are key to realizing the full potential of the C&C² approach. By better understanding how structures within components can be delimited, and by validating the applicability of the designation guide across domains, we can create a more efficient and effective product development process and lay the foundation for more advanced development in the future.

References

[1] Langeveld, L., 2011. Product Design with Embodiment Design as a New Perspective, in *Industrial Design - New Frontiers*, InTech, London, United Kingdom.

[2] 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*. Karlsruhe.

[3] He, B., Song, W., Wang, Y., 2013. A feature-based approach towards an integrated product model in intelligent design *69*, p. 15.

[4] He, B., Huang, S., 2016. Functional synthesis of mechanisms under cost consideration *230*, p. 91.

[5] He, B., Song, W., Wang, Y., 2015. Computational Conceptual Design Using Space Matrix *15*, 011004 (1-7).

[6] Gero, J.S., Kannengiesser, U., 2014. The Function-Behaviour-Structure Ontology of Design, in *An Anthology of Theories and Models of Design*, Springer London, London, p. 263.

[7] Andreasen, M.M., Hansen, C.T., Cash, P.J., 2015. *Conceptual Design: Interpretations, Mindset and Models*. Springer, Cham, Schweiz.

[8] Wölkl, S., Shea, K., 2009. A Computational Product Model for Conceptual Design Using SysML, in *Volume 2: 29th Computers and Information in Engineering Conference, Parts A and B*, ASME, San Diego, USA, p. 635.

[9] Beetz, J.-P., Schlemmer, P.D., Kloberdanz, H., Kirchner, E., 2018. Using the new working space model for the development of hygienic products, in *15th International Design Conference DESIGN 2018*, Dubrovnik, Kroatien, p. 985.

[10] Albers, A., Burkardt, N., Ohmer, M., 2004. Principles for design on the abstract level of the Contact & Channel Model, in *Tools and methods of competitive engineering: Proceedings of the TMCE 2004 Symposium, Lausanne, Switzerland*, Millpress, Rotterdam, p. 87.

[11] Albers, A., Matthiesen, S., 2002. Konstruktionsmethodisches Grundmodell zum Zusammenhang von Gestalt und Funktion technischer Systeme - Das Elementmodell "Wirkflächenpaare & Leitstützstrukturen" zur Analyse und Synthese technischer Systeme *54*, p. 55.

[12] Matthiesen, S., Grauberger, P., Bremer, F., Nowoseltschenko, K., 2019. *Product Models Embodiment Design - an Invetigation of Challenges and Possibilities*.

[13] Verein Deutscher Ingenieure e.V. Entwicklung technischer Produkte und Systeme: Modell der Produktentwicklung Blatt 1, 2019(2221).

[14] Albers, A., Wintergerst, E., 2014. The Contact and Channel Approach (C&C2-A): Relating a System's Physical Structure to Its Functionality, in *An Anthology of Theories and Models of Design*, Springer London, London, p. 151.

[15] Albers, A., Gladysz, B., Kniel, J., Aschoff, M. *et al.*, 2016. Integration von Versuchsergebnissen in C&C² - Modellen zur Wiederverwendung in der Produktgenerationsentwicklung am Beispiel eines trockenlaufenden Kupplungssystems, in *14. Gemeinsames Kolloquium Konstruktionstechnik 2016: Traditio et Innovatio - Entwicklung und Konstruktion, am 6. und 7. Oktober 2016 in Rostock ; Klaus Brökel, Jörg Feldhusen, Karl-Heinrich Grote, Frank Rieg, Ralph Stelzer, Peter Köhler, Norbert Müller, Gerhard Scharr (Hrsg.) ; Vorwort Klaus Brökel*, Shaker Verlag, Aachen, p. 10.

[16] Thau, S.L., 2013. *Heuristiken zur Analyse und Synthese technischer Systeme mit dem C&C²-Ansatz auf Basis von Entwicklungsprojekten im industriellen Umfeld = Heuristics to analyze and design technical systems with the C&C²-approach, developed within an industrial surrounding*. Karlsruhe, Karlsruhe.

[17] Albers, A., Deigendesch, T., Alink, T., 2008. Support of design engineering activity - the contact and channel model (C&CM) in the context of problem solving and the role of modelling, in *Proceedings of the DESIGN 2008*, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, p. 97.

[18] Porsche Newsroom. The body: Intelligent mix of materials for maximum strength - Porsche Newsroom. https://newsroom.porsche.com/en/products/taycan/body-18553.html. Accessed 7 February 2023.

[19] Lieury, A., 2013. Der Buchstaben-Zahlencode: Täuschung oder Wirklichkeit?, in *Ein Gedächtnis wie ein Elefant?*, Springer Berlin Heidelberg, Berlin, Heidelberg, p. 223.

[20] Peritz, G., 1918. Zur Pathopsychologie des Rechnens *61*, p. 234.