Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 100 (2021) 876–881

www.elsevier.com/locate/procedia

31st CIRP Design Conference 2021 (CIRP Design 2021)

Analysis of the variation of the element types of properties and functions of technical systems in product development practice

Albert Albers[a], Tobias Hirschter[a]*, Joshua Fahl[a], Simon Rapp[a]

[a]*Karlsruhe Institute of Technology (KIT) - IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 721 608-42371; fax: +49 721 608-46051. *E-mail address:* tobias.hirschter@partner.kit.edu

Abstract

In product development practice, it appears that engineering activities very often focus on the variation of the physical embodiment, as this is where the greatest and most obvious implications for the product seem to be perceived. Nevertheless, an empirical study revealed that variation in physical embodiment affects many other dimensions of a product, such as properties and functions. Within the scope of product specification, this requires a stronger differentiation of various dimensions of system elements. For this purpose, initial challenges and solution approaches in automotive product development practice are analyzed to gain a deeper understanding of the interrelationships of the variation of different types of system elements. The gathered findings and insights are then synthesized in a comprehensive systematic consisting of the structuring of elements of a new product generation or the reference system and an understanding of the set of elements in the Model of PGE – Product Generation Engineering. In summary, the differentiation of the variation types of the element types "property" and "function" is confirmed via the conducted case study. Further research should focus on supporting the product developer in identifying the alterations of the system elements by deriving the generic variation operator specifically onto the system elements of properties and functions of technical systems.

Keywords: PGE – Product Generation Engineering; Generic Variation Operator; Element Types; Set of Elements; Properties; Functions; Automotive Product Development Practice

1. Introduction an Motivation

Observations in product development practice indicate that the focus is very often directed at the variation of physical embodiment, since the greatest apparent impact on the product seems to be identified here. However, a Delphi study revealed that the variation of physical embodiment influences many other dimensions of a product, such as properties and functions [1]. In particular, the study participants see advantages in a "delta description" of a product generation compared to reference products (e.g. predecessors or even competing products). Furthermore, it should be emphasized that the conscious use of a reference system was identified as a significant criterion for success in product specification [2]. The use of reference system elements (RSE) in the product specification, however, requires a stronger differentiation of the various element types – e.g., properties, functions, physical elements, but also modular system elements, strategy elements, or production system elements. A consistent mapping understanding for the use of the reference system including the variation types of properties, functions and physical elements for the description of new development and carry-over shares of new product generations has the potential to effectively structure the product specification in the Early Phase. [1]

The present research work analyzes initial challenges and solution approaches of the variation of the element types of properties and functions of technical systems in automotive product development practice. In another publication at 31st CIRP Design Conference 2021 (cf. [3]), the findings of this analysis are synthesized and the *generic variation operator in the Model of PGE – Product Generation Engineering* [4] is applied to the *system elements of properties and functions* [3].

10.1016/j.procir.2021.05.028

2. State of Research

In order to clarify the research area, the generic reference product model for specifying complex products in the context of the Model of PGE – Product Generation Engineering will be discussed (cf. section 2.1). Subsequently, properties (cf. section 2.2) and functions (cf. section 2.3) of technical systems are examined.

2.1. Generic Reference Product Model for Specifying a Product Generation

The *Model of PGE – Product Generation Engineering* [5] according to ALBERS ET AL. describes product development on the basis of the principle assumption of a targeted use of already existing *reference system elements* (RSE) as the basis for the development of a new product. Starting from the so-called *reference system* [2], the RSE can be systematically transferred to a new product generation through the three variation types of *Principle* (PV), *Embodiment* (EV) and *Carry-over* (CV) *Variation* [4]. The *generic reference product model* [6] by ALBERS ET AL. is based on various concepts already established in practice and science that can be characterized by five success factors: *Systems thinking*, *stakeholder-centeredness*, *consideration of solution-open and solution-specific information*, *reference system elements*, and *basic product development activities*. The product model with its *three system views* (properties/functions/physical elements) and *several system levels* (supersystem(s), system, subsystem(s)) is integrated into the extended approach of the three central *systems of objectives*, *operation*, and *objects* [7]. Furthermore, the model includes the reference system R_n as a basis for the development the product generation G_n under consideration. Finally, the central development activities connect the different segments of the new model [6]. When transferred to the practical context, the developed model guides product developers to *systematize a product specification* from the very beginning and throughout the entire development process. In accordance with the integrated success factors, the model supports the management of complexity in the sense of *structuring homogeneous elements of a product specification* and linking them to central development activities. In addition to physical elements, these activities focus in particular and increasingly on *properties* (cf. Section 2.2) and *functions* (cf. Section 2.3) of those technical systems. [6]

2.2. Understanding of Properties of Technical Systems

In order to consider relevant stakeholders (especially customers and users) in the development of technical systems, numerous approaches in the literature describe a *property-based requirements definition* [8]. This approach allows the product developer to focus on *customer and user needs* at an early stage [9]. In this context, SCHUBERT [10] defines *properties* as objectively assessable design elements that represent the *embodiment* of a product and can be influenced by the product developer to satisfy needs. Furthermore, properties serve in the sense of *evaluation criteria* for the comparison of similar products and can be understood as *characterizing features* [11]. EHRLENSPIEL & MEERKAMM [12] describe as a property *"everything that can be determined by observations, measurement results, generally accepted statements, etc. of an object"*. According to WEBER [13], only the *characteristics* of a product can be directly influenced by the product developer, whereas properties result as consequential variables and describe the product behavior. Properties do not always refer exclusively to the overall product, but can be applied at any system level. Properties can also be classified – as shown in Figure 1 – in terms of *geometric/material properties*, *purpose or functional performance*, and the *relationship between the system and the environment* [12]. Properties of the geometric and material properties of a system (in the sense of characteristics, cf. [13]) can therefore be defined directly, while functional and relational properties can only be defined indirectly by the product developer. The *Contact, Channel and Connector Approach* (C&C²-A) further distinguishes between *embodiment, function* and *effect properties* [14]. The volume elements of the guiding support structures (LSS) and area elements of the effective surfaces (WFP) characterize *geometric, spatial or material properties*. LSS and WFP of a system in turn influence the functional and effective properties. The sum of all detectable effects involved in a function results in the functional properties of a system [14].

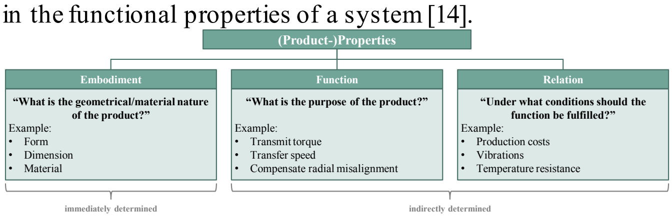

Fig. 1. Classification of (Product-)Properties [12].

2.3. Understanding of Functions of Technical Systems

In numerous places in the literature – with reference to the system concepts according to ROPOHL [15] – the functional dimension in the definition process of technical systems or products is emphasized beyond the structural aspect. FELDHUSEN ET AL. [16] attest that products serve to *"fulfill a function"* (in the sense of purpose with the objective of fulfilling a task). Accordingly, in product development, a function provides a *teleological sense* of the *existence* [17] of a *system*, but not a retrograde explanation of how a system works. FELDHUSEN ET AL. [16] understand a function generically as *"the general and intentional relationship between input and output of a system with the objective of accomplishing a task"*. EHRLENSPIEL [18] defines a function as a *property change* between an input and output state (cf. Figure 2). Thereby, a function can be formulated as a combination of a *noun* (denotes the turnover product) and *verb* (denotes the property change that occurs). The state of a turnover product is defined by the sum of its properties [18]. Here, the *property change* denotes the operation between the two states and thus represents a kind of process or procedure. The logical relationship between operations and states is represented by so-called *relations* [12]. The relation between input and output variables of a system is created by a technical process *"in which energies, substances and signals are conducted and/or changed"* [16]. These so-called technical functions serve in design methodology as a *"solution-neutral formulation of the intended (planned, designated) purpose of a technical entity"* [12].

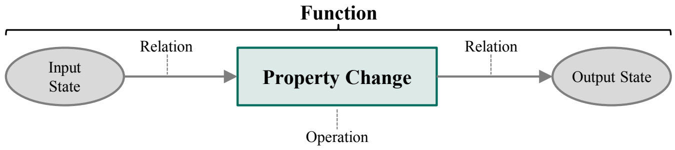

Fig. 2. Description Model for Functions [18].

3. Research Profile

First of all, the research objective and the derived research questions that structure the underlying research project are presented (cf. section 3.1). Furthermore, the research approach and environment are described (cf. section 3.2).

3.1. Research Objective and Questions

The *research objective* of this contribution is to *analyze the initial challenges and solution approaches* in product development practice *to gain a deeper understanding of the interrelationships of the variation of different types of system elements* such as *properties and functions of technical systems*.

The following *research questions* operationalize the superior research objective of the present work:

- Which *peculiarities and challenges* can be analyzed when linking the *variations of properties and functions* in *product development practice*, and what are possible *solution approaches*?
- How can *different types of reference system elements* (RSE) be differentiated and a *comprehensive set of system elements* be developed in the Model of PGE?

3.2. Research Approach and Environment

In order to build up a comprehensible chain of reasoning and to generate robust results, the procedure within the overarching research project was planned systematically. The *Design Research Methodology* (DRM) [19] forms the foundation. Hence, a first *Descriptive Study I* (DS-I, cf. Chapter 4) was conducted in this research work to analyze the challenges and possible solutions to variation of properties and functions of a technical system in automotive product development. The findings of the present research work were then synthesized in the *Prescriptive Study* (PS, cf. [3]) by a systemic approach in another publication at 31st CIRP Design Conference 2021 [3] that applies the generic variation operator in the Model of PGE [4] to the element types of the properties and functions of technical systems (cf. Outlook in Chapter 5).

4. Analysis of the Challenges in Product Development Practice and Solution Approaches towards the Variation of Properties and Functions (DS-I)

In order to gain a deeper understanding of the *research questions* (cf. section 3.1), the development of several, real vehicle projects at a *German Automotive Original Equipment Manufacturer* (OEM) were analyzed. The study and analysis were conducted over a period of *36 months*. The *Descriptive Study I* (DS-I) aimed at gathering insights concerning the variation of properties and functions in practice – synthesized by the *classification of different element types* of a new product generation or reference system in the Model of PGE (cf. section 4.2.1). Furthermore, the *understanding of the set of elements* in the Model of PGE (cf. section 4.3.1) is recapitulated.

4.1. Interrelationships of the Variation of Properties and Functions

In the following, the *three "classic" types of variation* (cf. section 2.1: CV, EV, PV) are each explained by way of example on the basis of observations in automotive product development practice. Hereby, the *carry-over variation* (CV) can be illustrated, for example, by taking over the *"brake" subsystem* from a modular system. The underlying solution principle of the disc brake, for instance, is available as a reference system element (RSE) and is transferred unchanged to the new system generation. Nevertheless, the CV of a physical element may require modifications in the connectors according to the requirements of system integration or changed boundary conditions at the interface to other system elements – such as the wheel hub. In the sense of the system theory, the carry-over of the *function "decelerate vehicle"* and the unchanged carry-over of the function attributes (in the sense of subfunctions or main/secondary functions, cf. section 2.3) can also be described here. If a subsystem is *varied in its embodiment* (EV), the underlying solution principle of the RSE together with all system-determining subsystem elements (incl. their inherent interactions) is transferred to the new system generation. Individual subsystem elements are, however, varied in their (embodiment) attributes – while retaining the solution principle – e.g. to increase competitiveness or performance and/or the quality of system fulfillment. Using the example of the *embodiment variation (EV) of the "brake"*, the geometry (characteristic diameter of the brake disc) can thus be varied from a physical point of view, which in turn can result in a change in the *property "braking behavior"* (e.g. reduction of braking distance by 5 [m] under standardized conditions). *Principle variation* (PV) uses a solution principle of an RSE as a starting point for adding and/or removing subsystem elements (including their inherent interactions) to create an elementary new solution principle. If, for example, the internal combustion engine is replaced by an electric motor in a new system generation of a vehicle, a fundamentally different technical solution is realized. The solution principle can sometimes fulfill a diversified output in other system contexts. A search for alternative solution principles can be supported, for example, by creativity techniques or the use of roadmaps. [4]

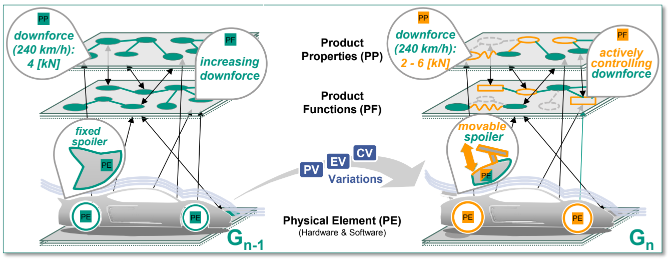

Fig. 3. Variation of Physical Elements and their Impact on Properties and Functions [4].

In Figure 3, the understanding of the explained "classic" types of variation in the system context is exemplarily applied to the variation of the spoiler of a sports car. In G_{n-1}, a fixed spoiler is used to generate a defined downforce. This fulfills the function *"increase downforce"* in the overall vehicle and may lead to an downforce (property) at 240 km/h of 4 [kN]. In the product generation G_n, the physical element is changed by means of PV. A new solution principle allows vehicle driving mode (Normal, Comfort, Sport) and speed-dependent both to adjust the downforce individually by controlling the spoiler pneumatically. In the vehicle as a whole, the new function *"control downforce actively"* can be established (variation of principle), which is generated from the combination of existing (e.g. *"increase downforce"*) and new (sub)functions (e.g. *"extend spoiler pneumatically"*). New properties can be captured in the spoiler system itself (e.g. actuating force), but at the overall vehicle level a change in the attribute of the downforce property can be detected. Thus, depending on the driving modes, downforce forces of 2-4 [kN] can be observed in the vehicle at 240 km/h. The example thus shows the effects of the „classic" variation types for physical elements on the variations of properties and functions (cf. Figure 3). [4]

4.2. Insights into the Classification of System Elements

The examples illustrate that a *large number of element types of a technical system* are *directly or at least indirectly affected and altered when physical elements are varied*. The interconnectedness and interaction is particularly evident in the course of the *variation of properties and functions*. The preceding example of brake development illustrates that the interaction between, for example, the material of the physical embodiment (e.g. gray cast iron or ceramic) and the associated robustness (e.g. in the case of stone impact) can itself be represented as an element. As already explained in section 2.1, only the elements of the reference system R_n are called reference system elements (RSE). *Only RSE can be mapped into the product generation G_n by means of the variation operator*, whereby likewise deliberately excluded elements are and remain modeled in the reference system. In the example of the *"brake" subsystem*, this means that the use of a ceramic disc brake, for example, based on a comprehensive investigation is not expedient due to the high sensitivity to stone impacts. Therefore a cast iron disc brake is used in G_n. Consideration of the element explicitly excluded for product generation G_n (ceramic disc brake) in the reference system R_n is essential in order to *present decisions transparently* and, if necessary, to *re-evaluate* them later in the development process or to validate them in (several) *engineering generations*.

4.2.1. Reference System Elements (RSE) in the Model of PGE

Reference system elements (RSE) can be *any type of engineering artifacts of previous developments*. Therefore, in the following, different, **possible aspects of reference system element types in the Model of PGE**, whose information can be determined or even reconstructed by an independent product developer in relation to a system, are explained by a classification or modeling approach. The systematic understanding in relation to the reference system enables the observer to understand the subsystems of a complex system (e.g. the brake of a vehicle) as one system element.

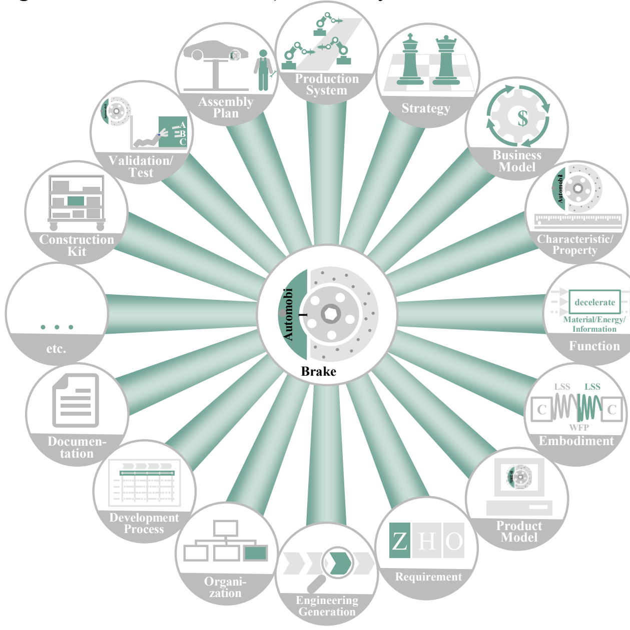

Fig. 4. Exemplary Excerpt of the Classification of Different Element Types of the Reference System or a New Product Generation in the Model of PGE.

In Systems Engineering, *system views and levels* are therefore distinguished in order to facilitate the development of a complex system. The example of *possible element types of the "brake" subsystem* in Figure 4 shows the different views and the artifacts generated in each view. In the reference system in the Model of PGE, for example, the *construction kit* from which the brake subsystem originates, can be regarded as a RSE. The modular system can be extended for a new product generation via variations. In the context of the *"overall vehicle system"*, specific, safety-relevant tests can sometimes be assigned to the *"brake" subsystem*, which are used to validate customer and/or user requirements. In the development of the production system of a product generation or the *subsystem* *"brake"*, for example, *assembly plans* are considered and varied in relation to maintenance or servicing. Furthermore, in the automotive industry, for example, *strategic quotas* of the carry-over variation of subsystems are planned in order to optimize the profitability of one or more product generations. Since the *"brake" subsystem* represents a wearing part of the vehicle in use, the variation of the *business model* can also be described, provided that a provider offers the customer free maintenance, for example. Another conceivable possibility is the variation of the *system models* (e.g. CAD model), which is influenced by the physical variation of the *"brake" subsystem*. In addition, variation can occur due to changes in the *tool chain*, shortening factor or software solution. In terms of fractality, subsystems in turn have their own specific *development processes*, so that in brake development, for example, varied reference, target and actual processes can be identified. The *documentation* of the *subsystem "brake"* is varied e.g. over the contained requirements and/or changes in system structure or the stakeholders. If *requirements* are varied (e.g. reduction of brake squeal), this often results in a variation of the *properties* or *characteristics*, *function* and *embodiment*.

4.3. Understanding of the relevant Sets of Elements

Intensive, reciprocal competitive analysis is common practice, particularly in automotive product development. For this purpose, vehicles of competing providers are acquired in order to analyze them in depth (e.g. by breaking down the physical embodiment into its subsystems). For example, a provider A is developing a new product generation G_n and has modeled in the reference system R_n a specific cast iron disc brake. The product developers synthesized for example from their analysis, by *partially reconstructing the system of objectives of the competitor vehicle,* that a *principally new function "recuperate vehicle energy"* relieves the hydraulic-mechanical brake and can thus be dimensioned more compactly. Solely by a *conscious decision of the product developer to consider and ultimately vary this knowledge element* in the new G_n, the element enters R_n as a RSE. Information is not only available to provider A through the purchase of a competitor's vehicle, but a *large amount of information* from, for example, product data sheets, press reports or operating manuals *is accessible*. A product developer can take the information about the optimum braking distance under standardized conditions from the product data sheet, for example. Nevertheless, the product developer must describe the information relative to the product generation in order to *generate knowledge through a necessary insight*. The *existence of information in the organization* is therefore *not sufficient to transfer this as an element into the reference system*. The strict separation of information and knowledge clarifies the extraordinary effort and, to a certain extent, creation in the modeling of the reference system by the product developer. The *application of information*, for example, from market research must be taken into account in the system context, since they *represent requirements or justifications* for the modeling in the reference system, if necessary. *Not all information must be available*, i.e., the real system of objectives information of the competing provider B exists, but is not generally accessible. By *(partially) reconstructing the system of objectives*, one could try to collect this information. In the example of technology development, one could try to reconstruct why there is a technology pioneer (element of the system of objectives).

4.3.1. Sets of Elements in the Model of PGE

Following on from the detailing of *possible element types in the reference system* in the Model of PGE using the example of the views of the development of the "brake" subsystem and the direct interactions in the development process, the **understanding of sets of elements in the Model of PGE** (cf. Figure 5) is discussed subsequently.

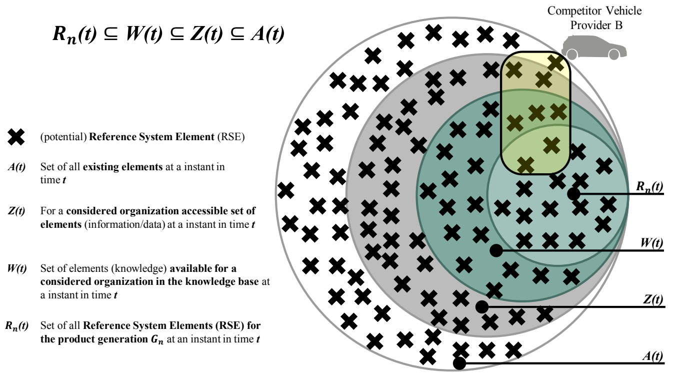

Fig. 5. Understanding of the Set of Elements in the Model of PGE.

The system theory (cf. [15]) states the *emergence of systems*, i.e., a system is more than the sum of its elements. Based on this, the existing *interactions* between elements are also understood as own system elements in the understanding of sets of elements in the Model of PGE. In the schematic Figure 5, any kind of system elements (including interactions) is represented by a "cross". For the project initiation of a product generation G_n, the corresponding **set of the reference system** $\boldsymbol{R_n(t=0)} = \emptyset$ is *empty* and must be actively modeled and filled by the product developer. The modeling of the **reference system set** $\boldsymbol{R_n(t)}$ should thereby be *purpose-bound*, *pragmatic* and *abbreviated*. In particular, the innovation potential and development risk of the product generation are influenced by the reference system. The *modeling and construction of the reference system* by the product developer is *a highly creative activity* (e.g. synthesis of findings from user studies, research, verification and validation of RSE) with significant effects on product development. Based on the activities it becomes clear that on the one hand sufficient knowledge of the product developer is necessary and on the other hand the *knowledge is person-bound*. By integrating further product developers into the problem-solving team, knowledge, in the sense of applied information from which knowledge is gained, can be added to the reference system. In this case, *applied information of knowledge* can be assumed to be part of the **knowledge base** $\boldsymbol{W(t)}$ of the problem solving team. The knowledge base is *independent of the product generation* G_n, because it can be used for product generations of *further product lines of the* *provider's product portfolio* as well. However, no (context) knowledge is yet available for the **set of accessible information** $\boldsymbol{Z(t)}$. The **set of all existing elements** $\boldsymbol{A(t)}$ is the limited set of all information that could be *accessible to an organization* through activities (e.g. research, reconstruction of the system of objectives, etc.), but is not yet accessible at the **instant of time** $\boldsymbol{t}$.

5. Summary and Outlook to Further Research

The conducted *Descriptive Study I* (DS-I) in the present research paper aimed at analyzing the *peculiarities and challenges* when linking the *variations of properties and functions* in *product development practice*. Therefore, the development of several, real vehicle projects at a *German Automotive Original Equipment Manufacturer* (OEM) were examined over a period of *36 months* to gain a deeper insight. Hence, the results of the case study in the automotive product development practice were synthesized in an *understanding of the types of reference system elements (RSE)* (e.g. properties, functions, physical elements, strategy, construction kit, engineering generations, etc.) and the *relevant set of elements* (e.g. set of reference system, knowledge base, set of accessible information, etc.).

In the subsequent *Prescriptive Study* (PS, cf. [3], a related publication at 31st CIRP Design Conference 2021), the gathered insights on system elements in the present research paper form the *precondition* for the *application of the generic variation operator in the Model of PGE – Product Generation Engineering* onto the element types of properties and functions of technical systems. The *specific deduction of the variation operator* may support the product developers in *identifying the alterations of the system elements* in relation to the developed understanding of the sets of elements. In addition, *linking the variation types of properties, functions, and physical elements* may initially reveal *preliminary patterns of "element-spanning" variation*. [3] Furthermore, the conducted analysis in automotive product development practice disclosed a *future need for a model-based approach in documenting and specifying the complex interrelationships and interactions of different types and sets of elements*.

References

[1] Fahl, J., Hirschter, T., Maier, H. and Albers, A. (2020) 'Cross-Industry Sectoral Study: Interactions and Challenges of Requirements Engineering in the Early Phase of Product Development', *DS 101: Proceedings of NordDesign 2020.* Lyngby, Dänemark, 12.-14-08.2020. Glasgow, Scotland, UK, The Design Society, n. p.

[2] Albers, A., Rapp, S., Spadinger, M., Richter, T., Birk, C., Marthaler, F., Heimicke, J., Kurtz, V. and Wessels, H. (2019) 'The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations', *DS 94: Proceedings of the Design Society: 22nd International Conference on Engineering Design (ICED19): Responsible Design for Our Future.* Delft, Netherlands, 05.-08.08.2019. Cambridge, UK, Cambridge University Press, pp. 1693–1702.

[3] Albers, A., Hirschter, T., Fahl, J. and Rapp, S. (2021) 'Application of the Generic Variation Operator in the Model of PGE – Product Generation Engineering onto the Element Types of Properties and Functions of Technical Systems', *Procedia 31th CIRP Design.* Enschede, Netherlands, 19.-21.05.2021. Amsterdam, Netherlands, Elsevier B.V.

[4] Albers, A., Rapp, S., Fahl, J., Hirschter, T., Revfi, S., Schulz, M., Stürmlinger, T. and Spadinger, M. (2020) 'Proposing a Generalized Description of Variations in Different Types of Systems by the Model of PGE – Product Generation Engineering', *DS 102: Proceedings of the DESIGN 2020: 16th International Design Conference.* Dubrovnik, Croatia, 26.-19.10.2020. Cambridge, UK, Cambridge University Press, pp. 2235–2244.

[5] Albers, A., Bursac, N. and Wintergerst, E. (2015) 'Produktgenerationsentwicklung: Bedeutung und Herausforderungen aus einer entwicklungsmethodischen Perspektive', *Stuttgarter Symposium für Produktentwicklung (SSP) 2015: Entwicklung smarter Produkte für die Zukunft.* Stuttgart, 18.-19.06.2015. Stuttgart, Fraunhofer Verlag, o. S.

[6] Albers, A., Hirschter, T., Fahl, J., Wöhrle, G., Reinemann, J. and Rapp, S. (2020) 'Generic reference product model for specifying complex products by the example of the automotive industry', *Digital Proceedings of TMCE 2020: Designing and engineering of smart systems.* Dublin, Ireland, 11.-15.05.2020. Delft, Netherlands, Delft University of Technology, pp. 353–370.

[7] Albers, A., Ebel, B. and Lohmeyer, Q. (2012) 'Systems of Objectives in Complex Product Development', *Proceedings of TMCE 2010 Symposium: Mobile and ubiquitous technologies for global product development.* Karlsruhe, 07.-11.05.2012. Delft, Netherlands, Delft University of Technology, pp. 267–278.

[8] Ponn, J. and Lindemann, U. (2011) *Konzeptentwicklung und Gestaltung technischer Produkte: Systematisch von Anforderungen zu Konzepten und Gestaltlösungen*, 2nd edn, Berlin, Heidelberg, Springer-Verlag.

[9] Wiedemann, G. E. (2014) *Ableitung von Elektrofahrzeugkonzepten aus Eigenschaftszielen*, Dissertation, München, TU München.

[10] Schubert, B. (1991) *Entwicklung von Konzepten für Produktinnovationen mittels Conjointanalyse*, Stuttgart, Poeschel.

[11] Hubka, V. (1984) *Theorie Technischer Systeme: Grundlagen einer wissenschaftlichen Konstruktionslehre*, 2nd edn, Berlin, Heidelberg, Springer.

[12] Ehrlenspiel, K. and Meerkamm, H. (2013) *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit*, 5th edn, München, Carl Hanser Verlag.

[13] Weber, C. (2012) 'Produkte und Produktentwicklungsprozesse abbilden mit Hilfe von Merkmalen und Eigenschaften: Eine kritische Zwischenbilanz', *DFX 2012: Proceedings of the 23rd Symposium Design for X (DfX).* Bamberg/Erlangen, 04.-05.10.2012. Hamburg, TuTech Verlag, pp. 25–62.

[14] Albers, A. and Wintergerst, E. (2014) 'The Contact and Channel Approach (C&C²-A) – relating a system's physical structure to its functionality', in Chakrabarti, A. and Blessing, L. T.M. (eds) *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations,* London, UK, Springer, pp. 151–171.

[15] Ropohl, G. (2009) *Allgemeine Technologie: Eine Systemtheorie der Technik*, Universitätsverlag Karlsruhe.

[16] Feldhusen, J., Grote, K. H., Göpfert, J. and Tretow, G. (2013) 'Technische Systeme', in Feldhusen, J. and Grote, K.-H. (eds) *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung,* 8th edn, Berlin, Heidelberg, Springer Vieweg, pp. 237–279.

[17] Chakrabarti, A. and Blessing, L. T.M., eds. (2014) *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, London, UK, Springer.

[18] Ehrlenspiel, K. (2009) *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit*, 4th edn, München, Carl Hanser Verlag.

[19] Blessing, L. T.M. and Chakrabarti, A. (2009) *DRM, a Design Research Methodology*, London, UK, Springer.