31st CIRP Design Conference 2021 (CIRP Design 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

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Abstract

In analogy to the research field of epigenetics in biology, engineering research in the Model of PGE – Product Generation Engineering according to ALBERS is concerned with the detection of phenomena of variation that can be observed not only in physical embodiment, but also in other system elements such as properties and functions. Based on the gathered findings and insights of the structuring of elements of a new product generation or the reference system and an understanding of the set of elements, the generic variation operator in the Model of PGE is applied onto the properties and functions of technical systems. The application of the generic variation operator supports the product developer in identifying the alterations of the system elements. In addition, linking the variation types of properties, functions, and physical elements initially reveals preliminary patterns of "element-spanning" variation. Further research should focus on systematically linking the carry-over and new development shares of properties, functions and physical elements, whereby insights on the innovation potential of a product generation and the underlying development risk may be evaluated.

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

1. Introduction an Motivation

Epigenetics is a field of research in biology that addresses the question of identifying the factors that temporarily determine the variation of a gene and thus the development and attributes of an organism or cell in its appearance (phenotype) [1]. The scientific discipline studies the changes in the mapping of genes that are not based on variation of a sequence of DNA (deoxyribonucleic acid) – for example, by mutation or recombination – and yet trigger changes in daughter cells. For a long time, researchers assumed that epigenetic information could not cross generational boundaries. However, because the DNA sequence is not altered, epigenetic effects cannot be detected and observed in the genotype, but can very well be observed in the phenotype (physical appearance) of different generations [2]. In analogy to epigenetics, research in the *Model of PGE – Product Generation Engineering* according to ALBERS [3] is concerned with the detection of phenomena of variation that can be observed not only in physical embodiment, but also in other system elements such as properties and functions. In the Model of PGE, for example, especially the generation-spanning development of functions and the phenomena of their targeted variation are explored as well as systematized in the product specification [4].

In the course of the present research work, the *generic variation operator in the Model of PGE* [5] is applied to the *system elements of properties and functions*. For this purpose, initial challenges and solution approaches in *automotive product development practice* were analyzed prior to that in another publication at 31st CIRP Design Conference 2021 [6].

2. State of Research

In order to clarify the research area, the Model of PGE – Product Generation Engineering will be examined (cf. section 2.1). Subsequently, the understanding of properties and functions of technical systems in the present research work are summarized (cf. section 2.2). Finally, the condensed results and insights of the analysis of the variation of the element types of properties and functions of technical systems in product development practice [6] are presented (cf. section 2.3).

2.1. Model of PGE – Product Generation Engineering

The *Model of PGE – Product Generation Engineering* according to ALBERS ET AL. [3] describes the creation of new products by two basic hypotheses:

- Each new *product generation* (G_n) is developed based on a *reference system* (R_n). Elements of the reference system originate from existing or already planned socio-technical systems and the associated documentation and serve as the starting point for the development of a new product [7].
- The technical subsystems of a new product are developed based on reference system elements *through Variation* [5].

The *Carry-over Variation* (CV) [5] is a *bundle of product development activities for the carry-over development* of a *system element* of a *new system generation*, in which the *underlying solution principle* of a reference system element (RSE) is *carried over* from the reference system into a new system generation *internally unchanged* (*with regard to its attributes*) and *adaptations* are only made at the *interfaces to other system elements* in accordance with the *requirements of system integration* and the *boundary conditions*. The *Attribute Variation* (AV) [5] is a *bundle of product development activities for the new development* of a *system element* of a *new system generation*, in which the *underlying solution principle* is *transferred* from a reference system element (RSE) from the reference system, *together with all inherent elements and links inside*, to a new system generation, *but its attributes are varied at least partially*. The *Principle Variation* (PV) [5] is a *bundle of product development activities for the new development* of a *system element* of a *new system generation*, in which the *underlying solution principle* is *transferred and varied* from a reference system element (RSE) of the reference system to a new system generation by *adding and/or removing inherent elements and links inside*. This *realizes a new solution principle* compared to the reference system element (RSE). [5]

The Model of PGE can be used to explain phenomena of development practice, such as the production of prototypes in the *Early Phase in the Model of PGE*, which is made possible by a high share of carryover variation [8]. The *product specification* belonging to the technical solution as part of the system of objectives contains, among other things, information regarding the technologies and subsystems used as well as their carryover and new development shares. It enables a valid evaluation of the technical system to be developed with regard to the relevant parameters such as producibility, the necessary resources or the technical and economic risk [8].

2.2. Understanding of Properties and Functions of Technical Systems

The present research work builds partly on the literature review by ALBERS ET AL. [6] and thereby conceives a **property** in product development as an *element type* of a technical system, by means of which the *behavior* can be described from, among other things, the customer's, user's and/or provider's point of view in a *defined context*. The *attribute of a property* is a *quantitatively and/or qualitatively ascertainable value*, which *cannot be influenced directly* by the product developer. A *property attribute* is *fractally* determined by at least one characteristic of the same technical system and its attribute. Furthermore, a *characteristic attribute* of a technical system is a *physical value* that *can be influenced directly* by the product developer and thus partially or completely determines the desired behavior (characteristic attribute) of the technical system [9]. Based on the literature review by ALBERS ET AL. [6] a **function** in the product development is understood as an *element type* of a technical system, by means of which a *cause-effect relationship* between a set of (initiating*) input variables* and (resulting) *output variables* as well as the (inherent) *state variables* can be described from a customer, user, provider and/or product developer view in a *defined context*. The *attribute of a function* results from the *hierarchical division into subfunction(s)* and/or *structural breakdown into main and secondary function(s)*. A *function attribute* is *fractally* determined by at least one subfunction or main function of the same technical system and its attribute. [10],[9]

2.3. Variation of Properties and Functions of Technical Systems in Product Development Practice

In order to gain a deeper understanding of the *peculiarities and challenges* when linking the *variations of properties and functions* in *product development practice*, the development of several, real vehicle projects at a *German Automotive Original Equipment Manufacturer* (OEM) were analyzed. The *Descriptive Study I* (DS-I, cf. [6], a related publication at 31st CIRP Design Conference 2021) and the interrelated analysis were conducted over a period of *36 months*. In summary, 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.) was obtained via the conducted case study in the automotive product development practice. This *understanding of system elements in the Model of PGE – Product Generation Engineering* serves as a *precondition* to effectively apply and apprehend the variations of properties and functions of technical systems. [6]

3. Research Profile

This chapter outlines the research objective and the derived research question (cf. section 3.1) that structure this contribution. Additionally, the research approach and environment are briefly discussed (cf. section 3.2).

3.1. Research Objective and Questions

The *research objective* of this contribution is to *apply the generic variation operator* in the Model of PGE – Product Generation Engineering *to the different element types of properties and functions* in order to *analyze the correlation of their carry-over and new development shares* to the variation of physical elements of a technical system.

The superior research objective is operationalized based on the following *research question*:

- How can the *peculiarities and challenges* of linking the *variations of different system elements* in product development practice be considered in *applying* the *generic variation operator* in the Model of PGE *onto the element types of properties and functions*?

3.2. Research Approach and Environment

The procedure within the overarching research project was planned systematically in order to build up a comprehensible chain of reasoning and to generate robust results. The foundation formed the *Design Research Methodology* (DRM) according to BLESSING & CHAKRABARTI [11]. Therefore, a first *Descriptive Study I* (DS-I, cf. [6] and section 2.3) was conducted to analyze the challenges and possible solutions to variation of properties and functions of a technical system in automotive product development in another publication at 31st CIRP Design Conference 2021 [6]. The findings were then synthesized in the *Prescriptive Study* (PS, cf. Chapter 4) in the form of a systemic approach in this research work. In the systematic, the generic variation operator in the Model of PGE is applied to the element types of the properties and functions. Finally, the developed systematic will be evaluated in the *Descriptive Study II* (DS-II) on the basis of the correlations of the carry-over and new development shares of properties and functions as well as possible patterns in case studies in the automotive product development in further research based on the results and findings of this work (cf. Outlook in Chapter 5).

4. Application of the Generic Variation Operator in the Model of PGE onto the Element Types of Properties and Functions of Technical Systems (PS)

Within the *Prescriptive Study* (PS), the *generic variation operator in the Model of PGE* (cf. section 4.1) is further *applied onto properties* (cf. section 4.1.1) *and subsequently onto functions* (cf. section 4.1.2) in order to answer the *research question* (cf. section 3.1).

4.1. Generic Variation Operator in the System Context in the Model of PGE

The *transfer and mapping of elements* from the reference system R_n to the product generation G_n is performed via the **generic variation operator** (cf. [5] and section 2.1) consisting of *carry-over variation* (CV), *attribute variation* (AV) and *principle variation* (PV), as shown in Figure 1.

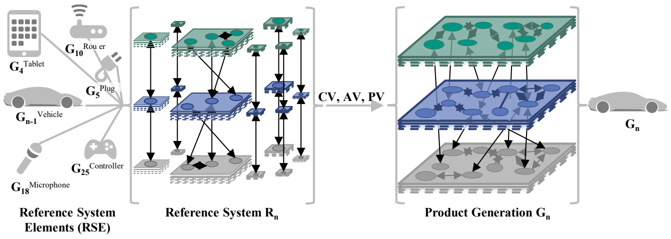

Fig. 1. Connecting the Understanding of the Reference System and Element Types (Properties/Functions/Physical Elements) to the Generic Variation Operator in the Model of PGE.

Based on the general system theory according to ROPOHL [12], the *generic variation types in the system context* can be described in the Model of PGE according to the following scheme and *graphically differentiated in visualizations*. Figure 2 introduces the system-determining subsystem elements, interactions and connectors as well as their variations. [5]

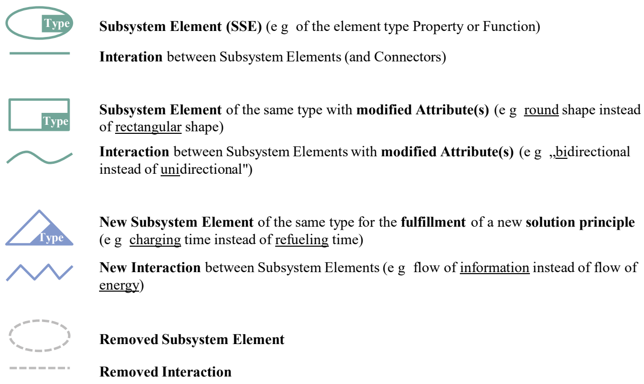

Fig. 2. System-theoretical Schematic for the Graphical Differentiation of the Variation-determining Elements and Interactions in the Model of PGE [5].

4.1.1. Application of the Generic Variation Operator to Properties in the Model of PGE

In the following Figure 3, the types of **variation of a property and their characteristics in the Model of PGE** are listed for generic description and graphical representation. The considered system element of the *element type "property"* is denoted in the following with E_j – their *realizing characteristics* following WEBER [13] with M_i. In the generic description of the variation types of a property, the connectors C_E (environment), C_{PS} (partner system) and C_V (viewer/observer) are considered in the following.

E_i	Considered **Property E_i** as System Element in Reference System R_n resp. Product Generation G_n
M_j	**Realizing Charateristic(s) M_j** of **Property E_i**
C_E	**Environment Connector** for consideration of environmental conditions (e.g. outside temperature, air humidity, etc.)
C_{PS}	**Partner System Connector** for consideration of the properties (as well as characteristics) of the partner systems (e.g. spring stiffness in the development of the damper in the spring-damper system)
C_V	**Viewer Connector** for consideration of the different perception in the perspectives on the property (e.g. customer, user, supplier, etc.)

Fig. 3. Introduction of the Elements for Generic Description of the Variation of Properties in the Model of PGE.

Target and actual properties must therefore be defined or evaluated in a specified context to ensure their uniqueness. In the *Environment Connector* (C_E), the defined environmental conditions, such as the outside temperature, are taken into account in order to make the target/actual comparisons of a property transparent. For this purpose, the *considered partner systems* and their influence on the property are to be considered as *connectors* (C_{PS}). Finally, the *observer/viewer* of the property is represented as a *connector* (C_V) in order to be able to compare different perceptions of the property (subjective perception). For example, a professional racing driver perceives the lateral acceleration of a sports car differently than an amateur driver who uses his vehicle exclusively for driving to work. The changes in the connectors have no influence on the variation type of the property – these can be identified on the basis of the changes in the characteristics.

4.1.1.1. Carry-over Variation (CV) of a Property

Figure 4 shows the understanding of the **carry-over variation (CV) of a property in the Model of PGE**. The property is connected to the connectors at the system boundary. When a property is carried over, the connectors can *change in their attributes* (e.g. temperature change). This means different results in the test case with the analysis, the properties, which *"adhere" to the technical system* do not vary. For example, the range of an electric vehicle can change at different external temperatures (including the interaction of the internal temperature of the battery) – but since the *trigger* is due to the external conditions (temperature), no variation in the property can be detected from the product development perspective.

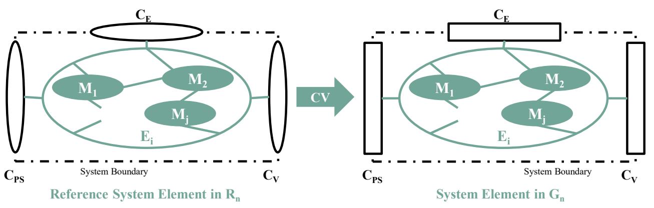

Fig. 4. Generic Representation of the Carry-over Variation (CV) of a Property in the Model of PGE.

4.1.1.2. Attribute Variation (AV) of a Property

In the case of **attribute variation (AV) of a property in the Model of PGE** (cf. Figure 5), the *attribute of a property* also changes independently of the external conditions. The variation of the property attribute is always due to a variation of *at least one determining characteristic and its interaction*. Thus, a variation in the attribute of a property (e.g. power of an electric motor) can be caused by a change in the physical values of the determining characteristics (wire cross-section [mm] in the rotor). The *"deliberate" attribute variation* is usually justified by the *desired increase in the performance of the system in order to ensure competitiveness*.

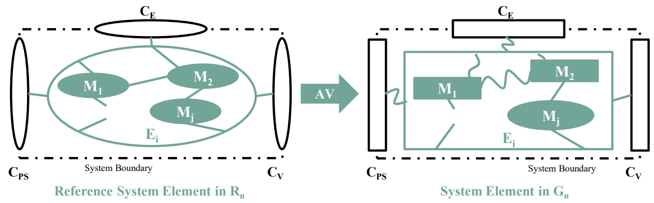

Fig. 5. Generic Representation of the Attribute Variation (AV) of a Property in the Model of PGE.

4.1.1.3. Principle Variation (PV) of a Property

Principle variation (PV) of a property in the Model of PGE involves the realization of a *new property or a new solution principle of a property* (cf. Figure 6). The principle variation is always *accompanied by new or omitted realizing characteristics and their interactions*. For the electric motor, for example, the addition of a characteristic in the software code for the control of *"energy recovery"* (recuperation) would mean a new property if the reference system element considered only took the power output into account.

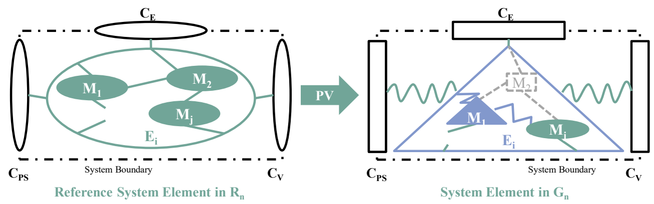

Fig. 6. Generic Representation of the Principle Variation (PV) of a Property in the Model of PGE.

4.1.2. Application of the Generic Variation Operator to Functions in the Model of PGE

In the following Figure 7, the types of **variation of a function in the Model of PGE** are listed for generic description and graphical representation. The considered system element of the *element type "function"* is denoted by Fct_i in the following explanations, their *attributes* – in the sense of *subfunction(s) or main/secondary function(s)* by f_j.

Fct_i	Considered **Function Fct_i** as System Element in Reference System R_n resp. Product Generation G_n
f_j	**Attribute(s) of Function Fct_i** in terms of **Subfunction(s) f_j** (hierarchical concept) and/or **main/sub-function(s) j** (structural conzept)
C_{Input}	**Input Connector** for consideration of influencing variables, parameters, boundary conditions and their interconnection at the system boundary of the input variables (e.g. quality of material/energy/information flow, probability of occurrence of events, etc.)
C_{Output}	**Output Connector** for consideration of the influencing variables, parameters, boundary conditions and their interconnection at the system boundary of the output variables (e.g. quality of material/energy/information flow, probability of occurrence of results, etc.)
C_{State}	**State Connector** for consideration of influencing variables, parameters, boundary conditions and their interconnection at the system boundary of the state variables (e.g. sequence of possible states, use cases, user journeys, etc.)

Fig. 7. Introduction of the Elements for Generic Description of the Variation of Functions in the Model of PGE.

For the generic description of the types of variation (CV, AV and PV) *three connectors* C_{Input}, C_{Output} and C_{State} are considered. In the *input variable connector* C_{Input}, the *influencing variables*, *parameters*, *boundary conditions* and *their interconnection at the system boundary* are accounted for to make the *traceability* and *comparability* of the *effect of a function transparent*. In relation to a *technical function*, the input variable connector contains, e.g. information about the *quality of the material/energy and/or energy flow*. In relation to a *product function*, C_{Input} contains, for example, the *specific probability of occurrence of initiating events of the product function*. Analogous to the input variable connector, the *output variable connector* C_{Output} considers the influencing variables and their interconnection at the system boundary of the output variables. In the *state variable connector* C_{State}, the influencing variables, parameters, boundary conditions and their interconnections are considered at the system boundary to describe, for example, the sequence of *possible states*, an *abstracted use case* or a *user journey*. The *changes within the three connectors have no influence on the variation of the function*, but the variation can be identified by the change of the determining subfunction(s) or main/secondary function(s).

4.1.2.1. Carry-over Variation (CV) of a Function

Figure 8 visualizes the understanding of the **carry-over variation (CV) of a function in the Model of PGE** on the basis of the reference system R_n into a product generation G_n. The inputs and outputs of the function Fct_i are connected to the corresponding *input connector* C_{Input} and *output connector* C_{Output}, respectively. The function Fct_i is also *directly linked to its state connector* C_{State} with respect to the state variables. In the course of the *carry-over variation of a function*, *only the connectors can change in their attributes* (e.g. quality of a material/energy/information flow or probability of occurrence of a discrete event). In the test case, for example, different *effects can be detected by the observer*, but the *functionality or the attribute of the function itself is not varied*. If, for example, the probability of occurrence of the event *"Wild animal jumps onto the road in front of the vehicle"* in the input variable connector C_{Input} changes, this does not change the fact (or functionality) that the vehicle nevertheless automatically performs emergency braking when the discrete event occurs. Since the effective relationship of the *system element "function"* also *remains unchanged internally* (with respect to its attribute of the sub- or main/side function(s) f_j) and thus the *identical solution principle of the underlying reference system element* from R_n is carried over, this is referred to as a *carry-over variation of the function*.

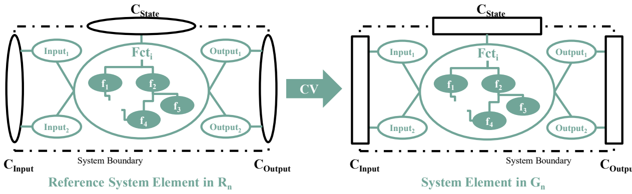

Fig. 8. Generic Representation of the Carry-over Variation (CV) of a Function in the Model of PGE.

4.1.2.2. Attribute Variation (AV) of a Function

The **attribute variation (AV) of a function in the Model of PGE** based on the reference system R_n into a product generation G_n is shown in Figure 9. The input variables and output variables of the function Fct_i are connected to their corresponding connectors analogous to the carry-over variation and the state variable connector is directly connected to the function. If the attribute of the *function changes independently of a change in the connectors*, this is called attribute variation of this function. The attribute variation of a function Fct_i is always *due to an at least partial variation of the inherent sub- or main/auxiliary functions* f_j or *their interactions inside the function* Fct_i. If, for example, the underlying effective relationship of the *function "control vehicle speed depending on distance"* is transferred from the reference system R_n and its inherent sub- or main/auxiliary functions are varied inside in such a way that the function *"control vehicle speed depending on topology"* can be realized in the new product generation G_n, this is a new development by variation of the attribute. The *desired or intended variation of a function by the product developer* is usually based on a *desired or intended increase in the performance and/or the quality of the function fulfillment*.

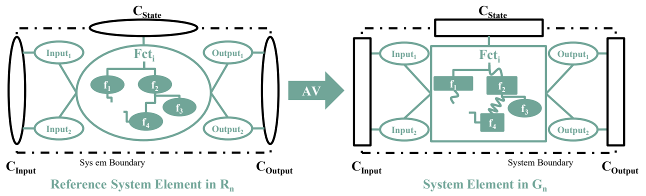

Fig. 9. Generic Representation of the Attribute Variation (AV) of a Function in the Model of PGE.

4.1.2.3. Principle Variation (PV) of a Function

Figure 10 visualizes the understanding of the **principle variation (PV) of a function in the Model of PGE** based on the reference system R_n into a product generation G_n. The input and output variables of the function Fct_i are connected to their corresponding connectors analogous to the carry-over and attribute variation and the state variable connector is directly connected to Fct_i. In the course of principle variation of Fct_i, the *underlying effective relationship of the reference system element is transferred to the product generation* G_n by *adding and/or removing inherent sub- or main/auxiliary functions* f_j or their interactions inside Fct_i. If, for example, one transfers the effective relationship of the function *"provide vehicle power take-off"* by adding and/or removing inherent sub-functions or main/auxiliary functions and varies these inside in such a way that the function *"control vehicle power take-off"* can be realized in the new product generation G_n, this is a new development by principle variation. As a result, a new effective relationship is realized compared to the reference system element. A principle variation (PV) of a function is always accompanied by an attribute variation (AV), analogous to the generic understanding in Section 2.1 – one also speaks of a new development of a system, starting with the principle variation of a function desired or intended by the product developer.

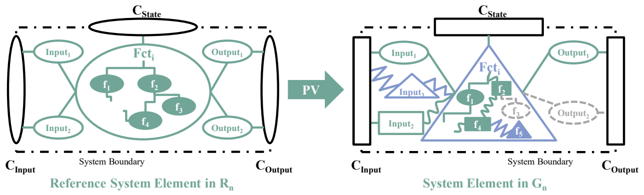

Fig. 10. Generic Representation of the Principle Variation (PV) of a Function in the Model of PGE.

5. Summary and Outlook to Further Research

In the conducted *Prescriptive Study* (PS), gathered insights on system elements (cf. [6], a related publication at 31st CIRP Design Conference 2021) formed the *premise* 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 in the present research paper. The product developer is supported in *identifying the alterations of the system elements* by this *application* and *specific deduction of the variation operator* in the *Model of PGE*. Furthermore, *preliminary patterns of "element-spanning" variation* are revealed by *linking the variation types of properties, functions, and physical elements* through the described systematic in this research paper and based on the *previous developed understanding of the sets of elements* [6].

In a subsequent *Descriptive Study II* (DS-II), the synthesized systematic will be evaluated in *further case studies in (automotive) product development*. For this purpose, an *initially conducted analysis from the authors' 30th CIRP Design Conference 2020 publication* [14] will be *revisited*, *extended* and *deepened* with the *generated findings* of the correlations and patterns of the carry-over and new development shares of properties and functions.

Further research may focus on *systematically linking the carry-over and new development shares of properties, functions and physical elements*, whereby insights on *the innovation potential of a product generation* and the *underlying development risk* may be effectively and quantitatively evaluated. Furthermore, the study identified *patterns of solution-open* and *solution-specific elements* that are particularly *critical for the success of product development* and exposed a need to strengthen the transparency and traceability by *Model-Based Systems Engineering* (MBSE) in product development practice. In addition, further *processual, methodological and structural approaches* must be identified for the specification of properties and functions in the Early Phase of PGE.

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