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Model of PGE – Product Generation Engineering by the Example of Autonomous Driving

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Abstract

Automotive product development is undergoing significant change: Autonomous driving is leading to altered customer needs that are decisive for competition and which established automotive OEMs must anticipate and systematically reflect in future product generations. To structure the provider side and manage product complexity, politics and industry, for example, classified autonomous driving into five levels (cf. Norm SAE J3016-2018) based on customer and user benefits. In order to counteract a complexity-induced "cost explosion", the functional implementation of autonomous driving must be planned across a provider's product portfolio. For the successful implementation of such development activities, methods and processes (e.g. "functional kit") must be developed to support the product developer.
The model of PGE – Product Generation Engineering according to ALBERS ET AL. describes every form of product development and enables the research and development of transferable methods. In this paper, a procedure model is developed based on the model of PGE for the systematic realization of requirements with severe effects on product complexity (e.g. redundant vehicle electrical systems, new E/E architectures) using the example of autonomous driving. The focus lies on the variation types at different product model views as well as the product function roadmap from which the functional product concept for future product generations can be derived on the basis of defined systems of objectives across the product portfolio. The procedure model aims to support the overarching planning of variations of physical subsystems by means of the functional product concept. The evaluation confirms a contribution to more efficient, customer-centric and cost-optimized product development through processes and methods of the model of PGE.

Keywords: PGE – Product Generation Engineering; Product Specification; Autonomous Driving; Product Properties; Functional Product Concept; Product Function Roadmap

1. Introduction and Motivation

The aim of product development is to develop functioning, producible and marketable products [1]. A balanced consideration of stakeholders is an essential success factor for effective product development. In order to consider the different perspectives in the early phase of the development of complex mechatronic products, a systemic understanding is necessary. The success factor of stakeholder integration is confronted with constantly shortening development cycles, increasing product complexity and the associated increasing development costs. The example of the automotive industry makes this clear: The pressure to differentiate on the path to autonomous driving and the networking of vehicles with each other and with their environment are challenges that need to be met at the same time. In recent years, German OEMs in particular have perfected approaches to efficient product development, such as the common parts strategy, the development of construction kits and platforms, which in some cases already provide the solution space for the development of new products. In equally efficient and effective product development, solution-open and solution-specific elements must therefore be taken into account in the early development phases in order to find the best compromise between them in

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the event of contradictory product requirements. One possibility for the solution-open modelling of the different stakeholder perspectives on a product is the definition of requirements on the basis of product properties and derived product functions. Product functions serve as "moderating" elements between solution-open and solution-specific elements. Autonomous or, in the first step, automated driving requires a considerable increase in complex product functions, the use of which must be planned across future generations of vehicles. If these functions are successfully fed into the respective system of objectives and implemented, the experience for customers, users and providers can be fundamentally improved at the same time. As a socio-technical system, product development comprises human capital with a focus on engineers and the technical resources for the development of product generations [2]. Therefore, the operation system in particular must be empowered and developed together with the product generations themselves in order to be prepared for the future. Therefore, this research project contributes to a more efficient, customer-centric and cost-optimized product development through processes and methods of the model of PGE.

2. State of Research

In the state of research, the basics of the model of PGE – Product Generation Engineering and Product Profiles are explained in the initial formation of the system of objectives. Finally, the automation levels of autonomous driving are introduced.

2.1. Model of PGE – Product Generation Engineering

The *model of PGE – Product Generation Engineering* describes the development of new products by two basic hypotheses ([3], [4]):

- Each product is developed on the basis of a *reference system*. Elements of the reference system originate from existing or already planned socio-technical systems and the associated documentation and serve as a basis and starting point for the development of a new product.
- The *subsystems* of a new product are developed on the basis of reference system elements through the activities *Carry-Over* (CV), *Embodiment* (EV) and *Principle Variation* (PV).

The model of the PGE can be used to explain phenomena of development practice such as, for example, the building of prototypes already in the *Early Phase of PGE*, which is only made possible by a high degree of carry-over variation [5]. The Early Phase of PGE is defined as *"a phase in the development process of a new product generation that begins with the initiation of a project and ends with an evaluated technical solution that ultimately covers the initial system of objectives with regard to its essential elements"*. 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 carry-over 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 [5]. By systematically using so called *engineering generations* [6], the state of the intended customer, user and provider benefit modelled in the product profile can be determined throughout the development process. Engineering generations structure the development of a product generation and increase thereby customer-orientation.

The *variations* in the model of the PGE are activities that consist of several activities of product creation, whereby the type of this set of activities usually differs depending on the variation type [7]. The different types of variation are reflected in different ways in the *effect structure* of the subsystems of a new product generation, compared to the effect structure of the underlying reference system elements [8]. Targeted variations can be derived, among other things, by comparing desired functions and functional states with those already implemented in potential reference system elements [9].

2.2. Product Profiles in the Formation of the Initial System of Objectives

The *initial system of objectives* contains the first basic objectives for the development of a product and is developed at the beginning of the product development process [10] and continuously concretized [11]. The finding of *product profiles* is a central activity of product development according to ALBERS ET AL. The product profile supports a holistic, systemic goal setting of a product generation. This is *"[...] a model of a bundle of benefits that makes the desired provider, customer and user benefits accessible for validation and explicitly defines the solution space for the design of a product generation"* [12]. Objectives, requirements and boundary conditions of all relevant stakeholders as well as product properties, central functions and application scenarios of the product generation represent essential elements of the product profile. The degree of technical detail should be limited, while the core technologies must be specified to assess the technical feasibility (central activity in the product specification). Furthermore, the product profile contains information on the technical and economic feasibility and the associated development risk [12]. As one of the most common models, the *Munich Product Concretization Model* [1] separates objectives of the development in the requirements space from possible implementations in the solutions space. The considerations on strategic product identification by means of a product profile can be converted into a first, development-related product description and transferred into a *reference product model* (cf. Figure 1). The product model supports the concretization in the technical problem-solving process from a rather *solution-open to a solution-specific description* of the product generation [13]. The reference product model (cf. Figure 1) is divided into the *property*, *functional* and *physical views* [14]. Also within the views different degrees of detail can be defined, which are determined by the specificity of content and process. For uniform hierarchization the system levels *System of Systems* (SoS), *Supersystem*, *System* and *Subsystem* are considered. In addition, specific information from reference products and systems can be analyzed and abstracted. The most abstract view is the description of solution-open **product properties** that can be experienced by the customer. According to ALBERS ET AL., a product property is a property of a technical product that can be used to describe the behavior that can be experienced from the point of view of the customer, user and/or provider. Product properties enable (similar) products to be *compared subjectively*, sometimes *objectively*, and thus to describe *product differentiation*. (Product) *characteristics* and their *attributes* serve the modelling of the *experienced behavior* ((product) properties) by the product developer. (Product) characteristics form the design level of the product developer and can be *defined directly* (design characteristic) and indirectly (functional characteristic and relation characteristic) by the product developer. The experienced behavior is continuously validated by comparison with the parameters that can be influenced by the product developer [15]. The *concretization* of product properties can be realized via product functions. A **product function** is a function of a technical product that describes *solution-open* an *effect relation* over *partial functions* (and their technical functions) on a customer and/or user-oriented level between an *initiating event* and a *desired result* [15, 16]. Due to the higher level of content detail, product functions can be interpreted as solution-specific compared to product properties [13, 17]. A promising way to meet challenges of defining product concepts is a function-orientation and thereby *functional concepts*, which enable customer-orientation in the development of complex mechatronic products such as vehicles [16]. The highest degree of content detail is found at the level of the *physical subsystems* (i.e. hardware and software components). These serve the *realization* of product properties and product functions.

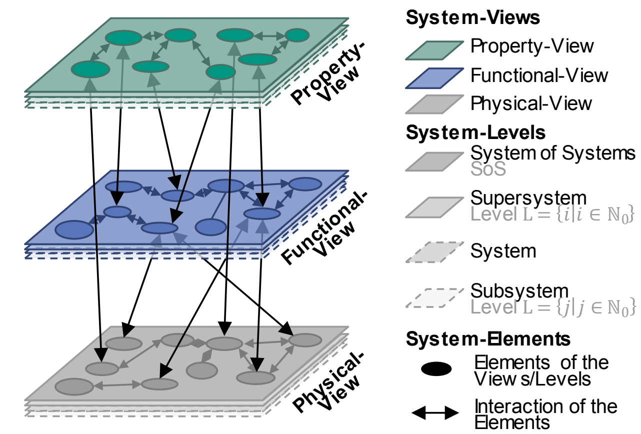


Figure 1: Reference Product Model for Specifying a Product Generation in the Model of PGE [14].

Following similar approaches, the reference product models of GAUSEMEIER ET AL. [18], EHRLENSPIEL AND MEERKAMM [19] and EIGNER ET AL. [20] apply levels to differentiate solution-open and solution-specific elements, which are connected by concretizing and abstracting activities.

2.3. Autonomous Driving

The human driver still has an outstanding ability to perceive the vehicle environment, to drive the vehicle stably on the road and, last but not least, to react to current traffic situations with adequate driving maneuvers [21]. In the context of increasing driving comfort, efficiency and safety in traffic, science and industry worldwide are researching functions and their physical systems of autonomous driving in order to enable vehicles to do precisely this and to relieve people [22]. *Autonomous driving* describes the movement of a road vehicle – which is not tied to a dedicated infrastructure (e.g. rails) – which is exclusively operated by humans by entering or adapting a mission (task of transporting goods, persons or vehicle itself from start to destination) or which independently assigns a mission [21]. An autonomous vehicle must therefore by definition plan its own behavior and control the driving task by means of an independent control system. The driving task is divided into three levels: *navigation*, *guidance* and *stabilization* [21]. With the standard J3016, SAE INTERNATIONAL has developed a terminology for terms that refer to automobiles in road traffic for autonomous driving and classified them in six levels between *"no automation"* and *"autonomous driving"* according to current practice in the automotive industry (cf. Figure 2). At each level, the functional aspects are defined and thus a step-by-step progress is described by the so-called *automation levels 0 to 5*. The classification clarifies for each level what role (if any) the driver or human plays in performing the dynamic driving task while a function of the various automation levels is in operation [22].

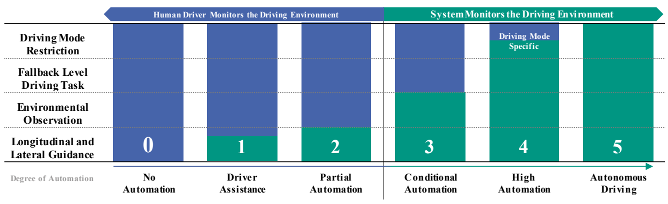


Figure 2: Level of Autonomous Driving according to SAE J3016-06/2018 [22].

3. Research Questions and Approach

In this chapter, the research objective of the contribution and the derived research questions for structuring the research process are outlined. The research environment and the research approach are then presented.

3.1. Research Objective and Questions

The *research objective* of this contribution is to ensure the systematic linking of solution-open elements of the product profile with the types of variation of physical subsystems in the *Early Phase of PGE – Product Generation Engineering* in order to support the product developer in the efficient and effective development of the specification of a product generation by suitable processes and methods. The focus in the process model should be on the definition of functional product concepts across the product portfolio, which can be derived from a "functional kit" on the basis of the overarching defined system of objectives. In this article, the superior research objective is structured on the basis of the following *research questions*:

- Which potential **reference system** elements are **available** within the **specification of a product generation** and how is their **information used**?

- What **special features** characterize **product properties** and **functions** in **automotive development** in relation to the model of PGE?
- How can these be **modelled in the model of PGE**, how can **product specifying activities** be derived and **supported methodically**?
- How can **product generations** with their different **variants** be differentiated across different **providers** and their **product lines**, **product lifecycle**, in an **ontology** in the model of PGE?
- How can **information** from **previous product generations** be used to efficiently **plan the variation shares** of physical subsystems **across product lines** based on the **functional product concept**?

3.2. Research Environment and Approach

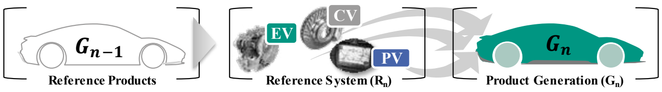
The concept development phase is complex and usually encounters many challenges that require immediate attention and action. However, problems that have already been solved and their documented causes and solutions represent a valuable knowledge base that can be used when new problems arise (e.g. [24]). In order to gain a deeper understanding of the research questions, the early phase of the development of a real vehicle project at a German OEM was analyzed. In this understanding, the Early Phase of PGE comprises the process and all activities necessary to specify a vehicle project sufficiently after project initiation with regard to the technologies used, producibility as well as economic and technical feasibility. After completion of the Early Phase of PGE, all product properties are defined, the functional product concept is defined according to the solution-open specifications, and the implementing physical subsystems are identified.

The case study was conducted over a period of 18 months. In a preliminary study, the triggers for the variation of physical subsystems of a real vehicle project were identified at the level of product properties and product functions (cf. Chapter 4). In an in-depth document and object study, properties profiles, functional product profiles and technical product descriptions of two vehicle projects were linked and compared across the three levels of the reference product model in the model of PGE [14] (cf. Chapter 2.2). In particular, the relationships between the types of variation and possible patterns were examined (cf. Chapter 5.1). The results and findings of these linkages were then transferred to a procedure model for product portfolio-spanning planning of variation shares and methodically supported (cf. Chapter 5.3). The systematic realization of requirements with serious effects on product complexity (e.g. redundant wiring systems, new E/E architectures) – supported by the product portfolio-spanning planning of variation types in the model of PGE – is then evaluated using the example of autonomous driving (cf. Chapter 5.3).

4. Preliminary Study in Automotive Product Development

Identifying the *triggers of a new development* (PV, EV) of physical subsystems a *product generation in development* G_n of an automobile manufacturer was analyzed. The evaluated product generation is a successor with new core technology. In order to limit the complexity regarding the origin of several reference products, the study only refers to one reference product, the previous product generation G_{n-1}. Since the analyzed properties as well as functions refer to the overall system level, they are called product properties and product functions. For the document analysis, the *property profile* of the engineering generation, which contains all target values of the considered properties on the overall system level (product properties), the *functional product profile* with all relevant functions directly perceptible for the customer and a *technical product description* with the listing of all physical subsystems and components, were considered.

The overall vehicle system was divided into **452 physical subsystems** (exclusively hardware components) on the basis of an existing reference structure and analyzed. Referenced to the predecessor generation G_{n-1}, a share of **15% carry-over variation (CV)**, a share of **71% embodiment variation (EV)** and a share of **13% principle variation (PV)** can be recorded (cf. Figure 3). The product generation G_n is realized with a new drive technology, which explains the high proportion of new developments.



Types of Variation	Absolute Share	Percentage
Carry-over Variation (CV)	69	15 %
Embodiment Variation (EV)	323	71 %
Principle Variation (PV)	60	13 %
Number of Physical Subsystems	452	100 %

Figure 3: Variation Shares of Physical Subsystems of a Real Vehicle Project in Relation to the Predecessor Product Generation.

Once the variations of the subsystems have been determined, a *comprehensive participatory observation* is performed independently of the consideration of product attributes and product functions. This is made possible by the fact that the participating observers are members of the product development committee, which is leading in the conceptual work. In the further analysis of the *triggers of variations in physical subsystems*, the *changes*[1] *in product properties* and *product functions* – in particular due to new drive train technology, increased *functional quality*, adaptation due to a modified *overall system package*, further development of the *subsystem across product lines*, *cost* and *weight reduction* – were examined.[2]

A 91% change in a **product property** (e.g. reduction of wind noise leads to an EV of the roof system) is achieved by a new development (PV, EV) (see Figure 4). It is worth mentioning the 18% PV, which is particularly due to the new drive technology, which sometimes creates new properties such as charging power or electrical range (69%). The EV share of 73% is due to physical subsystems made of G_{n-1}, which

[1] *Change* here includes adding, removing, as well as changing the characteristic (existing property) or effect (existing function).

[2] In this case, only the initiating product properties and functions for the variation of the physical subsystems were analyzed.

have already been further developed in other OEM product lines. In addition, they are justified notably by the improvement of the functional quality (e.g. reduction of the acceleration time from 0-100 km/h) and the reduction of costs and weight (54%). The high proportion of new developments in physical subsystems (PV, EV) of 85% for product properties that are not changed compared to G_{n-1} be initially striking. For "unchanged" properties in relation to the reference product, the proportion of EV of the associated subsystems is nevertheless 84.5%. This is due in particular to the further development of the subsystems in other product lines (35%) or adjustments due to the changed package (28%). Consequently, this indirectly triggers a new development that is not directly attributable to the variation of a property. In addition, new developments are made to compensate for disadvantages (e.g. high body structure, poorer transversal dynamic properties) due to the new drive technology (29%). In addition, the influence of the variation of a subsystem on the change of a product property is evaluated. While the PV of a physical subsystem almost exclusively leads to a change in the product properties (97%), an EV in 48% of the considered product properties does not result in a change in the characteristics.[3] The high proportion suggests the quality of the process for defining product properties according to HIRSCHTER ET AL. [25], which is used in the company in question. Conversely, this means that only a very small proportion of the PV cannot be experienced by the customer. This variation of the physical subsystems is driven in particular by a further development of already existing subsystems from G_{n-1} in other product lines (35%) and a targeted reduction of costs and total weight (36%) and thus has no direct effect on product properties.

Product Properties → Physical Subsystem
„Identification of Triggers for the Variation of Physical Subsystems"

	Variation Physical Subsystems		
Product Properties	CV	EV	PV
Not a Change	15 %	84,5 %	0,5 %
Change	9 %	73 %	18 %

Product Properties ← Physical Subsystem
„Influence of Variation Types on Product Properties"

	Product Properties	
Variation Physical Subsystems	Not a Change	Change
CV	56 %	44 %
EV	48 %	52 %
PV	3 %	97 %

Figure 4: Relationship between Alterations in Product Properties and Variation Types of Physical Subsystems.

Considering the influence of the **product functions** on the variation types of the physical subsystems, it can be observed that the functional change (new product function, increase in the quality of a product function or modification of the technical implementation) leads to a new development share (PV, EV) of 90% (cf. Figure 5). Nevertheless, a cumulative PV and EV of 86.5% can also be determined when a product function is carried over from G_{n-1}. Similar to the influence of properties, the proportion of EV is very high (85%) when a product function is carried over. The high proportion of new developments, despite unchanged product function, can be attributed to weight and cost reductions as well as the new drive concept, analogous to the product properties. Figure 5 on the right again shows the reverse analysis. Identifying the triggers for the variation of physical subsystems is more revealing when considering the effects of the variation types and the change in product functions. At the level of product functions, the PV of a physical subsystem leads to a functional change in 93% of the cases considered. On the other hand, an EV causes a change in the product functions only in 52% of cases. Thus, the percentage is only slightly above the CV (49%), which leads to a change in function. The new development share (43%), which has no effect on product functions, is to be regarded in particular as adjustments to physical subsystems from the reference product G_{n-1} (56%). In addition, further developments of the physical subsystems already implemented in other product lines of the product portfolio, such as sensors for driver assistance systems (34%) and measures to reduce costs and weight (10%), lead to further EVs that also have no effect on product functions.

Product Function → Physical Subsystem
„Identification of Triggers for the Variation of Physical Subsystems"

	Variation Physical Subsystems		
Product Function	CV	EV	PV
Not a Change	13,5 %	85 %	1,5 %
Change	10 %	73 %	17 %

Product Function ← Physical Subsystem
„ Influence of Variation Types on Product Functions"

	Product Function	
Variation Physical Subsystems	Not a Change	Change
CV	51 %	49 %
EV	48 %	52 %
PV	7 %	93 %

Figure 5: Relationship between Alterations in Product Functions and Variation Types of Physical Subsystems.

As a **result of the study** it can be stated that further information on the realizing functions and properties of a subsystem is necessary to identify triggers for the variation of subsystems. On the basis of the high correlation of the principle variation with the change of properties and functions in particular, it can be concluded that conclusions about the variation of physical subsystems can be drawn on the basis of properties and functions. Knowledge sharing is regarded as one of the most important issues in knowledge management, for improving efficiency, quality and time to market in new product development [26] and for overcoming challenges of sustainability aspects within a company [27]. Since this knowledge, in the sense of solution-open product definition, is already available very early in the development project, it should be used to assess the realization uncertainty and plan the engineering generations. Properties are particularly suitable for the specification of a product generation in the Early Phase in the model of PGE. Since the EV shares of the physical subsystems for properties and functions were comparably large for both the planned target change and the planned non-change, the variations of properties and functions must be further analyzed. However, the existing variation types (CV, EV and PV) cannot be transferred to properties and functions without adaptation. In particular, the embodiment variation (EV) aims at the existence of hardware-based systems. Furthermore, especially in the Early Phase of PGE, the search for (especially internal) reference products to minimize the high share of new development (PV + EV in total 85%) must be methodically supported.

[3] A distinction must be made between the *properties of the overall product* (product property), such as acceleration behavior, and the *properties of the hardware component*, such as the diameter of the crankshaft. The properties of the hardware components, on the other hand, are always changed per definition by the principle variation. [15]

5. Model of the PGE – Product Generation Engineering by the Example of Autonomous Driving

In this chapter, the results and findings from the case study in automotive product development are translated into variation types of product properties and product functions in the model of PGE – Product Generation Engineering. Subsequently, a procedure model for the product portfolio spanning planning of variation shares is developed, methodically supported and applied using the example of autonomous driving.

5.1. Variation Types of Product Properties and Functions in the model of PGE – Product Generation Engineering

5.1.1. Definitions of Variation Types

In order to be able to describe the carry-over and new development of product properties, product functions and physical subsystems holistically, a more abstract understanding of variation types is required. In addition, the term *embodiment variation* is only appropriate for the level of the physical subsystems. According to ZINGEL [28], the embodiment merely describes the physical structure of a technical system. In a more recent study [29], based on empirical observation, the term of embodiment variation (EV) is broadened to the more abstract concept of **attribute variation** (AV) in order to fully encompass attributes of elements in a system context instead of solely the physical embodiment. Thus the following three types of variation can be distinguished [29]:

The **carry-over variation (CV)** of a system element describes the *carry-over of an existing solution principle* that is carried over from a reference system element in the *reference system* to a new product/system generation and *adapted* to the *requirements of system integration* and *boundary conditions at the interfaces*. The adjustments should be minimized as much as possible, so that the *original attributes of the solution principle* are *not fundamentally changed*.

The **attribute variation (AV)** of a system element describes the *new development of a system element* in which a *known solution principle* is *transferred from a reference system element* or the *general state of knowledge* from the reference system to a new product/system generation. This variation of the *determining attribute(s)* is *varied* while *maintaining the solution principle* in such a way that an *increase in competitiveness*, *performance* and/or *quality of system fulfillment* is generated.

The **principle variation (PV)** of a system element describes the *new development of a system element* by *adapting* a system element that *fulfils a diversifying output in other contexts*, or by *systematically searching for alternative solution principles* (e.g. through creativity techniques or the use of system roadmaps to generate a new output in a new product/system generation). A principle variation always *goes hand in hand with an attribute variation (AV)* – one also speaks of a *new development of a system, beginning with the principle variation* (influenceable by product developers).

5.1.2. Application of defined variation types

Subsequently to the preliminary study in chapter 4, the *effects of variations of properties on the decisions for variation of subsystems* are comprehensively investigated to gain insights for the process model and method development for the product portfolio-spanning planning of variation shares. For this purpose, a distinction is made as to whether a property attribute should change in relation to the previous generation G_{n-1} or should remain equally significant. The property attributes contained in the property profile are to be understood as target attributes, that is, the formulated differentiation from a reference product. At this stage, the effect of a variation of a subsystem on the change of properties is analyzed. Subsequently, the steps are analogous for the interaction between functions and physical elements. With the exception of the product line-spanning further development of the subsystem, all triggers can be directly justified on the basis of the variation of properties and functions. In most cases, however, the variation of properties and functions can be deduced indirectly. A **conflict-free listing** of the **product profile** (*80 product properties*), a **functional product profile** (*50 product functions*) as well as the division of the entire vehicle based on the **technical product description** into *452 physical subsystems* formed the data basis. In the study, the variations of the product properties and functions were first determined. The *variation types were then linked across all levels*. An n×n link between the levels is theoretically possible, but the assignment of one element to a maximum of three elements of the other directly adjacent level was restricted in order to manage the resulting paths.

By linking the variation components across all levels, **894 paths were identified** (cf. Figure 6). The results show that 97% of a variation of attribute (AV) of a product property is realized by a principle variation (PV) of a product function linked to PV of a physical subsystem. A PV of a product property is mainly composed of the combination of an AV or carry-over variation (CV) of a product function with an AV of a physical subsystem. The combination of an AV of a subsystem with a functional CV forms the most frequent path to the carry-over of a product property.

Principle Variation (PV) of a Product Property: Linkage Paths	Absolute Share	Percentage
PV-PV-PV	62	96,88 %
PV-PV-AV	1	1,56 %
PV-PV-CV	-	0 %
PV-AV-PV	-	0 %
PV-AV-AV	-	0 %
PV-AV-CV	1	1,56 %
PV-CV-PV	-	0 %
PV-CV-AV	-	0 %
PV-CV-CV	-	0 %
∑	64	100 %

Attribute Variation (AV) of a Product Property: Linkage Paths	Absolute Share	Percentage
AV-PV-PV	20	4,59 %
AV-PV-AV	50	11,47 %
AV-PV-CV	4	0,92 %
AV-AV-PV	1	0,23 %
AV-AV-AV	167	38,30 %
AV-AV-CV	22	5,05 %
AV-CV-PV	6	1,38 %
AV-CV-AV	147	33,72 %
AV-CV-CV	19	4,36 %
∑	436	100 %

Carry-over Variation (CV) of a Product Property: Linkage Paths	Absolute Share	Percentage
CV-PV-PV	1	0,25 %
CV-PV-AV	78	19,80 %
CV-PV-CV	8	2,03 %
CV-AV-PV	2	0,51 %
CV-AV-AV	70	17,77 %
CV-AV-CV	16	4,06 %
CV-CV-PV	-	0 %
CV-CV-AV	185	46,95 %
CV-CV-CV	34	8,63 %
∑	394	100 %

Figure 6: Frequency of the Paths linking the Types of Variation across the Views of Product Properties, Functions and Physical Subsystems of a Real Vehicle Project.

The analysis of the shares of the linkage paths alone does not lead to significant results, but these serve as *indicators to identify correlations between types of variation at all levels*. A PV of a product function is implemented to 95% by a new development (PV, AV) of physical subsystems. Conversely, 90% of PVs of physical subsystems lead to a functional PV. For this reason, the PV is an indicator for a high proportion of new developments in physical subsystems. It also shows that 51% of the CV of physical subsystems are linked to a functional CV. Consequently, a *correlation* can be identified *between the complexity of the variations of product functions* (as triggers) and the *complexity of variations of physical subsystems*. A PV of a product property (here mainly induced by the new drive concept) is implemented 98% by a functional PV and 97% by a PV of a subsystem. In addition, the majority of physical PVs lead to property PVs (67%), physical AVs to property AVs (52%) and CVs to CVs (56%). An analysis of the links between the functional and property levels shows that 68% of physical PVs and 56% of functional CVs implement property PVs.

The **results of the case study** show that there is also a correlation between the complexities of the variations in product properties, functions and physical subsystems. Variations of product properties (analogous to product function) can be seen as triggers for variations on other levels of the reference product model. The identified dependencies between variation types of all levels of the product model motivate the investigation of variations of product properties and functions in the Early Phase of PGE. By determining the variation types of the two levels, the variations of physical subsystems can be planned across product lines and product generations.

5.2. Nomenclature in the Model of PGE

As a basis for the procedure model, the fragmented representations of the set of relevant concepts as well as their relationships are formally arranged in a **nomenclature** in order to be able to specify the references in the procedure model more precisely. A contribution from FAHL ET AL. [16] has shown, that functional concepts can be modelled on different levels of abstraction in the model of PGE: *product portfolio* (and *its product lines*), *product generation* (and *its variants*) and product function (and its subfunctions). This understanding of abstraction is transferred to differentiate product or engineering generations from each other. The **nomenclature in the Model of PGE** can be described as follows.

Product generation $G_i^{k,u,a,p,v}$

for **generation** $i \epsilon \mathbb{N}$ and <u>optional</u> `Strings` $\boldsymbol{k,u,a,p,v}$ ***customers*** $\boldsymbol{k \epsilon \{k_1, \dots, k_h\}}$, ***users*** $\boldsymbol{u \epsilon \{u_1, \dots, u_l\}}$, ***providers*** $\boldsymbol{a \epsilon \{a_1, \dots, a_m\}}$, ***product lines*** $\boldsymbol{p \epsilon \{p_1, \dots, p_q\}}$ *and* ***variants*** $\boldsymbol{v \epsilon \{v_1, \dots, v_r\}}$ *where* $\boldsymbol{h, l, m, q, r \epsilon \mathbb{N}}$.

Particular product generations:

- $G_1^{k,u,a,p,v}$: <u>*First product generation*</u> of a new product of the product line p with its variants v on the market. The first product generation has no direct predecessor.
- $G_n^{k,u,a,p,v}$: Product generation of the product line p with its variants v <u>*in development*</u>, which will be launched on the market next (at current time).
- $G_{n-1}^{k,u,a,p,v}$: Current product generation of the product line p with its variants v <u>*on the market*</u>
- $G_{n+1}^{k,u,a,p,v}$: Product generation of the product line p with its variants v <u>*in development*</u>, which will be launched on the market next but one (at current time)

Analogously, the nomenclature can be transferred to

Engineering generation $E_{i,j,\dots}^{k,u,a,p,v}$ *and*

Reference system $R_{i,\dots}^{k,u,a,p,v}$

for **generations** $i, j \epsilon \mathbb{N}$ and <u>optional</u> `Strings` $\boldsymbol{k,u,a,p,v}$ ***customers*** $\boldsymbol{k \epsilon \{k_1, \dots, k_h\}}$, ***users*** $\boldsymbol{u \epsilon \{u_1, \dots, u_l\}}$, ***providers*** $\boldsymbol{a \epsilon \{a_1, \dots, a_m\}}$, ***product lines*** $\boldsymbol{p \epsilon \{p_1, \dots, p_q\}}$ *and* ***variants*** $\boldsymbol{v \epsilon \{v_1, \dots, v_r\}}$ *where* $\boldsymbol{h, l, m, q, r \epsilon \mathbb{N}}$.

The optional parameters for customers k and users u are omitted in the following chapters of this paper to reduce the complexity and to increase comprehensibility. However, a description of a product generation by all parameters is still possible. Figure 7 shows an example of the nomenclature in the model of PGE that is relevant for this research work. Here, two product lines p_1 and p_2 of a provider are shown, which in turn represent coherent product generations. Below, the engineering generations of product line p_1 are schematically depicted.

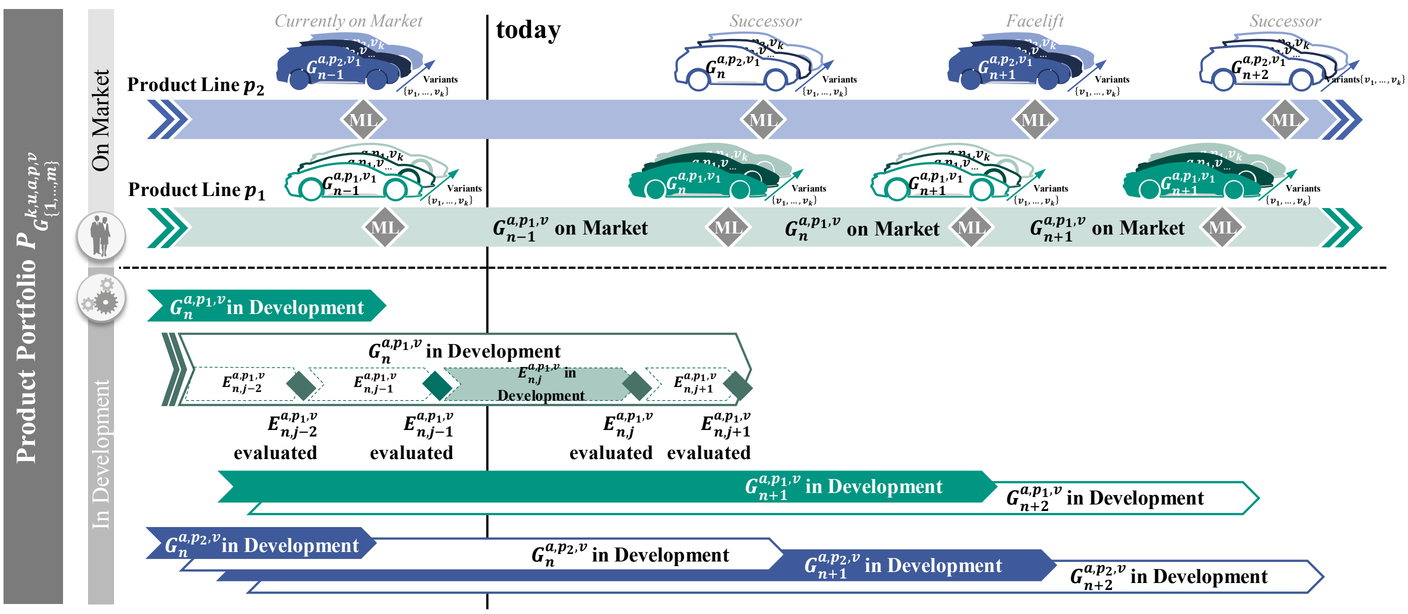


Figure 7: Exemplary Product Portfolio of an Automotive Provider in the Model of PGE – Product Generation Engineering.

5.3. Procedure Model and Method Development for Product Portfolio-spanning Planning of Variation Shares

Based on the results and findings from Chapters 4 and 5.1 as well as the requirements for specifying a product generation (using the example of the automotive industry), a *procedure model* was developed (cf. Figure 8). Starting from the **product profile analysis** (*Phase I*), a **product portfolio-spanning definition of the functional product concept of a product generation** (*Phase II*) is carried out, followed by the **development of the concepts of individual product functions** (*Phase III*) in order to finally improve the **planning of the variation of physical subsystems** in the model of PGE (*Phase IV*). The procedure is not to be regarded as strictly sequential.

5.3.1. Product Profile Analysis (Phase I)

In order to structure the formation of the *initial system of objectives*, the *product profile* of a product generation $G_i^{a,p,v}$ is initially created. A model relevant in practice for this is the **property profile**, in which the differentiation of a product generation is described on the basis of product properties derived from selected elements of the reference system $R_i^{a,p,v}$ [25]. The desired *product differentiation* can be recorded on the basis of the *variations of product properties* (carry-over (CV), attribute (AV) and principle variation (PV)). The property profile has the claim to depict the planned customer and user benefit solution-open – whereby the provider benefit results from the prioritization of product properties and the realization by product functions and physical subsystems. Since the solution-open concretization of the product profile goes hand in hand with the product specification, alternative solutions at functional and technical level must be identified at an early stage and existing solutions assigned. *Critical concretization paths* (cf. Chapter 5.1) with a high proportion of principle variation (PV) on all levels must be identified, particularly for product development. Since several *product generations of the product portfolio* can be found in product development, *product profiles must also be planned across the board* in the formation of the initial system of objectives. On the one hand, this aims to achieve synergy effects in the technical implementation and on the other hand to ensure the target differentiation of the product lines and generations of a provider's product portfolio.

If one considers an OEM product generation $G_i^{a,p,v}$ in which the drive concept changes from conventional (internal combustion engine) to electrical, new vehicle features must be planned and defined (PV of product properties). For example, the charging behavior can be defined as a property target on the basis of the attribute *"State-of-Charge (SOC) charging time from 5% to 80% in 25 minutes"*. The property to be defined can in turn be derived and justified on the basis of elements of the reference system (faster charging than the competition). In addition, the definition of the attribute of automation level 3 (partially automated driving [23], cf. Chapter 2.3) for the product property *"autonomous driving behavior"* represents an attribute variation (AV) at the overall product level if $G_{i-1}^{a,p,v}$ has an automation level 2 (partially automated driving). If the product property autonomous driving behavior is broken down further, the product property *"self-contained interaction behavior of the vehicle with its environment"*, for example, can represent a principle variation (*fractal character of the product properties*). These new development parts of the product properties can be graphically supported together with the part from carry-over variation (e.g. "display behavior" with identical characteristics as in the predecessor product generation $G_{i-1}^{a,p,v}$ via polarity diagrams or relevance evaluations [25].

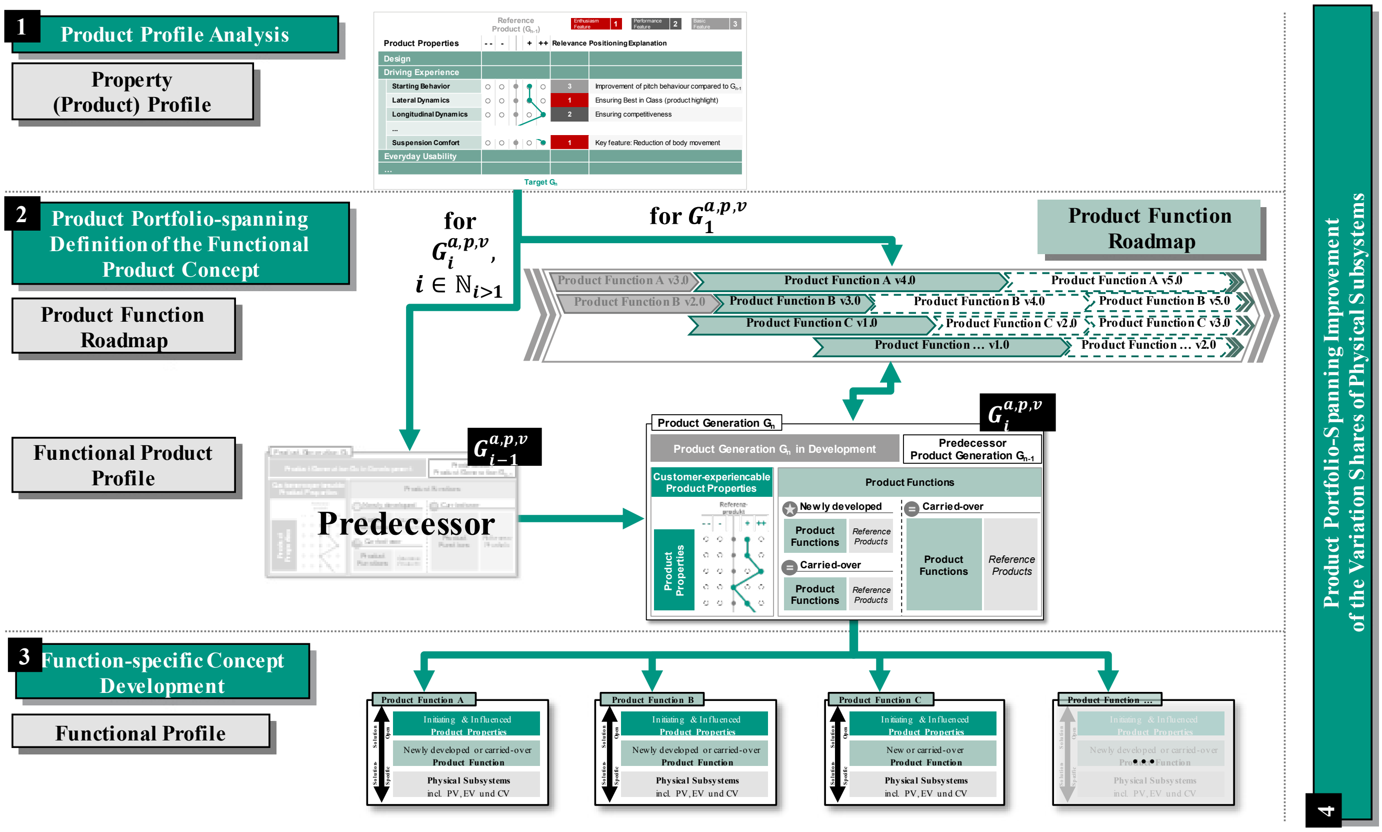


Figure 8: Procedure Model for Product Portfolio-spanning Planning of Variation Shares in the Model of PGE.

5.3.2. Product Portfolio-spanning Definition of a Functional Product Concept of a Product Generation (Phase II)

The differentiation of a product generation $G_i^{a,p,v}$ in the property profile (cf. phase I) can be further concretized via product functions or a holistic, **functional product concept**. The *overarching interactions of the set of all product functions* describe the functional product concept of a product generation $G_i^{a,p,v}$ from the *customer and user point of view*. The functional product concept of a product generation from the *provider's point of view* also includes the *function-specific concepts of each product function* and describes them solution-specifically. In the sense of the PGE – Product Generation Engineering, product functions are also developed in generations. This is done based on the reference system via new development through a principle variation (PV) (e.g. *new product function "traffic jam pilot"*) or an attribute variation (AV). The extension of the functional scope of a product function *"Active Lane Keeping"* in the context of Autonomous Driving, whose effect-relationship between initiating event and desired result are extended by the inclusion of route data or a *functional quality increase* of the time-of-day-dependent traffic sign recognition, is to be understood as an AV. The functional part of the new development is supplemented by the part of carry-over variations of the reference system and thus of the carried-over effect-relationships between initiating event and desired result of product functions.

The **product function roadmap** is to be understood as a *"functional kit"* in which *all product functions of a provider's entire product portfolio* are integrated. The product functions developed in generations that are or have been currently on the market, are in development or have only been planned for the future regardless of a specific product generation are depicted in it (cf. Figure 9). If a product function is not transferred to the product function roadmap via the PV in a specific product or engineering generation, product functions can also be developed independently of product generations due to their solution-open nature. Several factors were identified that may trigger the development of a product function. In principle, these factors comprise endogenous (e.g. innovations and technology, corporate strategy or brand DNA) and exogenous factors (e.g. trends and scenarios, markets and customers, competition and laws).

The **functional product profile** [25] of a product generation $G_i^{a,p,v}$ supports the elaboration and solution-open description of the *functional product concept* on the basis of the variation types of the product functions and in relation to their solution-specific reference system elements – e.g. the predecessor product generation $G_{i-1}^{a,p,v}$.

Alternative 1: Definition of the Functional Product Concept for $G_i^{a,p,v}$ for $i \epsilon \mathbb{N}_{>1}$:

If the considered product generation $G_i^{a,p,v}$ does not represent the first product generation of a new product line $G_1^{a,p,v}$ or $i \neq 1$, the *functional product concept of the predecessor product generation* $G_{i-1}^{a,p,v}$ forms the *definition basis*. The defined new development (PV, AV) and carry-over variations (CV) of the product properties from *phase I* are linked with the initially transferred product functions from the predecessor product generation $G_{i-1}^{a,p,v}$. In a first step, *superfluous product functions* can thus be removed from the functional product concept of the $G_i^{a,p,v}$ product generation under consideration so as to *avoid functional overfulfilment*. Subsequently, the previously inadequately addressed variations of product properties in the property profile must be realized via additional product functions. The *product function roadmap* is used to derive product functions from other product lines of the product portfolio or *planned functional attribute or principle variations* (AVs or PVs) into the functional product concept of the product generation $G_i^{a,p,v}$.

In analogy to the example described in *Phase I* of the development of a new successor product generation $G_{i+1}^{a,p,v}$ with electric drive train and the associated PV *"charging behavior"*, there are initially no product functions of the predecessor $G_{i-1}^{a,p,v}$ that can realize such product properties for the customer or user. Therefore, the development of new product functions (related to the reference product $G_{i-1}^{a,p,v}$) is required. However, if the provider, for example, already offers or develops an electric vehicle on the market in another product line, product functions such as *"time-controlled AC/DC charging"* are available in the central, functional planning and steering tool – the *product function roadmap* – and can be derived from there into the functional product concept. By taking into account further internal reference system elements of the provider, the necessary functional PV for the product property "charging

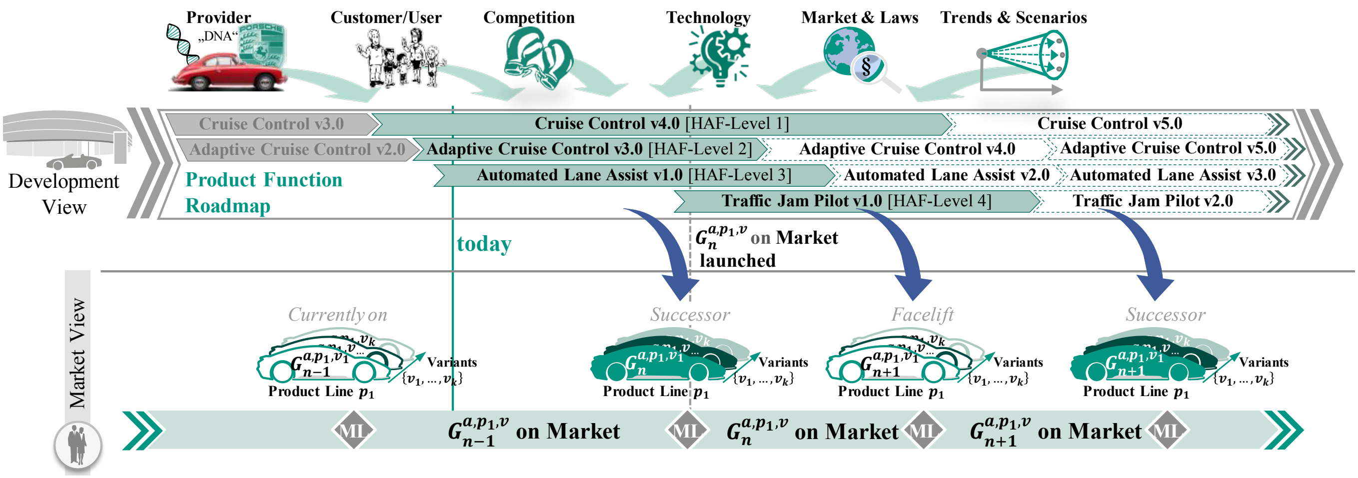


Figure 9: Schematic Representation of the Product Function Roadmap in the Model of PGE – Product Generation Engineering.

behavior" becomes a functional AV or even a CV from another product or engineering generation of the product portfolio. The reference product AV or CV is no longer the predecessor $G_{i-1}^{a,p,v}$, but the product or engineering generation of the product line from which it is varied. If there are no product functions in an OEM's product portfolio either on the market or in development to achieve the property of *"autonomous driving behavior"* specified in the property profile, new product functions (PVs) can be derived from the product function roadmap that are already planned for future product generations (e.g. "*traffic jam pilot*"). Provided that the product function as a PV has not yet been developed or planned in any development or product generation, as a rule no function-specific concept has yet been worked out. This function-specific concept development takes place in the following *Phase III*.

Alternative 2: Definition of the Functional Product Concept for $G_1^{a,p,v}$:

Assuming that a *new, first product generation* $G_1^{a,p,v}$ of a new *product line* p with its *variants* v is developed, this product line by definition has no direct predecessor product generation. Accordingly, there is also no functional product concept of $G_{i-1}^{a,p,v}$ as a basis for linking with the variation types of the product properties. For this reason, the functional product concept of the first product generation $G_1^{a,p,v}$ can be derived directly from the *product function roadmap*. The product developer selects from the *entire functional range of the product portfolio* those product functions which contribute to the required attributes of the product properties until all product properties are adequately addressed or necessary functional PVs identified. Regardless of whether *alternative 1 or 2* is used, an automobile manufacturer offering several product lines on the market must define the *functional product concepts* of the individual *product lines* and *variants* of a product generation accordingly so that the product generations do not *cannibalize* each other.

5.3.3. Function-specific Concept Development of Product Functions (Phase III)

In order to define an overarching, functional product concept, the *function-specific concepts of the individual product functions* must be specified during development. For this purpose, the *influence or initiation of the event* by the customer/user, environment and product as well as the provider are defined. In addition, *product requirements and boundary conditions* for events and product functions themselves are concretized from the linked product properties by means of their features and characteristics. Furthermore, the *desired experience* of the product function is defined, which realizes the behavior of the product properties. The effect-relationship between event and desired result is detailed in *subfunctions*, which in turn can be described via an effect-relationship between event and result from the customer/user perspective. From this, *input/output variables* (material/energy/ information) of *technical functions* as well as the *physical subsystems for implementation* in the overall product can then be derived. The physical subsystems are defined by the mapping of the reference system via the operators of principle variation (PV), attribute variation (AV) and carry-over variation (CV).

A function-specific concept development of the functional principle variation (PV) *"traffic jam pilot"* can take place according to the variation of the product property *"autonomous driving behavior"* on automation level 3 described as an example in *Phase 1*. When activated by the user via the steering column lever on motorways and federal highways with structural separation, the **traffic jam pilot** assumes the driving task. This is possible if the vehicle can *"swim" in traffic jams* or *convoy traffic at less than 60 km/h*, for example. In these situations, the traffic jam pilot controls the subfunctions of *starting*, *accelerating*, *steering* and *braking the vehicle* and also *controls demanding situations* induced by the environment (inciting vehicles) [30]. The product function uses interconnected technical functions and ultimately physical subsystems (e.g. *front camera*) to measure and control the distance to vehicles in front. The experience of the desired functional result that the customer/user perceives through the product properties describes the taking over of control of the vehicle, so that the user can permanently take his hands off the steering wheel and devote himself to another occupation. A camera in the cockpit detects when the driver gets tired or falls asleep. In this case, a warning is issued and the driver is prompted to take control of the vehicle [31].

The *development of function-specific concepts* for all product functions is methodically supported by a **solution-specific functional profile** as a tool for sensitizing the cross-departmental contributors to the interfaces at an early stage and creating transparency with regard to the consistency of product properties across product functions to the physical subsystems [25]. In the functional profile of the traffic jam pilot, the *initiating* and, if necessary, further *influenced product properties* (such as driving comfort, environmental compatibility, user experience, etc.) are specified in detail as well as the *carry-over and new development shares* of the implementing physical subsystems (based on reference system elements). The functional profiles of product functions, which are mapped into the product generation or engineering generation by means of AV or CV and are consequently located in the product function roadmap, already exist. These must be adapted to the *specific changes* in the product or development generation under consideration in a *project-specific way*.

Formally, the functional product concept from the customer's and user's point of view is supplemented by the function-specific provider's point of view and thus completely defined. In the following *Phase 4*, an *improvement of the linked variation shares across the different levels* takes place, so that in particular the variation types of physical subsystems can be improved across the product portfolio taking into account *cost and development efficiency*.

5.3.4. Improving the Planning of Variation Shares in the Model of PGE – Product Generation Engineering (Phase IV)

In order to make the *formation of product portfolio-spanning system of objectives* including the definition of product profiles and functional product concepts usable for the development of physical subsystems, *variation shares have to be planned accordingly across generations*. The development of, for example, a *laser scanner* (for e.g. a *traffic jam pilot*) for dynamic detection of the vehicle environment represents a principle variation compared to a *front camera*. Laser scanners for **autonomous driving** are increasingly used in vehicles fulfilling automation level 3 or higher. Their development costs are many times higher than those of a conventional front camera. If, for example, an automation level 2 product function is developed in $G_i^{a,p,v}$, the individual decision-making is usually made in favor of using a front camera. Knowing that an automation level 3 and corresponding product functions (e.g. *motorway pilot*) are planned for subsequent generations or other product lines, the decision to *reduce overall development costs*, *application synergies* or, for example, *functional expansion* can also be made by using a laser scanner in $G_i^{a,p,v}$. In order to be able to make these decisions across the board, knowledge of both solution-open and solution-specific elements as well as their interactions across the (functional) product portfolio is necessary in early development phases. For this reason, decisions at all levels must be made transparent and usable across the product portfolio – a suitable instrument for this is the *product function roadmap*.

6. Evaluation and Discussion of Results

The procedure developed and corresponding methods were used in the **automotive industry** and subsequently in the **special mechanical engineering** (bucket wheel excavators) and **household electronics** (extractor hoods) sectors. Their added value has been particularly evident in complex contexts, such as the project of **autonomous driving**. The starting point is the overall product and the *comprehensive planning of product generations* (sometimes several product lines) of one provider. By means of a solution-open description, differentiation targets can be defined against reference system(s) without too much limitation of the realization space. By linking solution-open objectives with product functions, physical subsystems and their variation shares, the technical feasibility and economic efficiency can be demonstrated early in the project. For this purpose, the use of product functions and physical subsystems can be planned across generations in the product portfolio. In addition, the *early validation of the benefit promise* (in the product profile) is supported by the *systematic planning of the implementation of automation levels*. The solution-open description of the perception of automation levels on the basis of product properties in a property profile limits the solution space without anticipating the technical solution. Using *methods and processes* based on the model of PGE – Product Generation Engineering, the use of automation levels can be functionally planned across product lines and product generations. The proof for the *efficient, customer-centered and cost-optimized product specification* on the basis of the procedure model, in which the provider benefit is improved, is given below.

The effects of the application of the procedure model for product portfolio-spanning planning of variation shares on the variation shares of product functions and physical subsystems are shown in Figure 10. The variations of the product properties are not subject to any change, since the product profile analysis (Phase I) specifies the variations in relation to the reference product of the predecessor product generation $G_{i-1}^{a,p,v}$ and was not adapted. The *application of the procedure model* shows that the product portfolio-spanning definition of the functional product concept of a product generation (Phase II) reduces the *complexity of the variations of product functions*. By *using the product function roadmap*, in which all product functions of a provider's entire product portfolio are integrated, product functions can be transferred from other product lines of the provider. Thus, for example, a functional principle variation (PV) from the reference product $G_{i-1}^{a,p_1,v}$ becomes an AV from the reference product $G_{i-1}^{a,p_2,v}$. The *quantitative analysis* shows that there are *no more PVs at the product function level* and that the proportion of carry-over variations (CV) of product functions has increased by 9%. This in turn has an effect on the proportion of variations in physical subsystems. As a result, the *share of new developments* in physical subsystems is *reduced* by 13%. In particular, the proportion of cost-intensive principle variations (PV) is falling from 13% to 6%.

Variation Types of Physical Subsystems	Product Generation-Specific		Product Portfolio-Spanning
	Percentage		Percentage
Carry-over Variation (CV)	15 %	+13%	28 %
Attribute Variation (AV)	71 %	-6%	66 %
Principle Variation (PV)	13 %	-7%	6 %

Variation Types of Product Functions	Product Generation-Specific		Product Portfolio-Spanning
	Percentage		Percentage
Carry-over Variation (CV)	15 %	+9%	43 %
Attribute Variation (AV)	28 %	+29%	57 %
Principle Variation (PV)	38 %	-38%	0 %

Figure 10: Effects of Product Portfolio-spanning Planning on the Variation Shares of Product Functions and Physical Subsystems.

As a result of the application of the procedure model, the *linkage paths* of the variations of all levels as well as the relationships between the respective levels have also changed. The share of CVs of physical subsystems in AVs of product functions (+14%) and in AVs of product properties (+21%) has increased overall. In addition, the PVs of physical subsystems have a greater impact on the variations in product properties due to the process model (+19%).

The procedure model for planning variation shares across product portfolios leads to a *reduction in the functional PVs* and an *increase in the functional AVs*. This in turn leads to a *reduction in the new development shares* (PV, AV) of physical subsystems. The necessity of defining variation types of product properties and product functions is justified by the results of this study. A product portfolio-spanning planning of variation shares supports *handling the complexity of the development task*, so that the *basic development effort can also be reduced*.

7. Outlook and Future Research

The *increase in efficiency through the application of the procedure model in automotive practice* was demonstrated by the study. In addition, there is still a need for future research into the *definition of a generic reference structure* for automotive development in order to systematically support the linking of product properties, product functions and physical subsystems without restricting excessively the creative, individual part of the creation process. In addition, the use of the *procedure must be analyzed in depth across all industries* in order to prove *quantitative added value* (in terms of reduced costs and new development shares) in addition to the qualitative confirmation available. The survey was conducted using *text-based elements* in the form of *Excel sheets* and *requirements management tools*. The product specification on the basis of text-based elements on all levels means an immense expenditure of time in the development, with which a high probability of the loss of information is present. Therefore the *support of the product specification* in the Early Phase of PGE – Product Generation Engineering has to be examined by *model-based approaches*.

In addition, further approaches (*processes, methods and tools*) must be identified for the product properties and functions that further support the product specification. Furthermore, the study identified *linking paths of solution-open* and *solution-specific elements* (product properties, product functions and physical subsystems) that are particularly *critical for the success of product development*. A qualitative comparison of the paths with elements that have PVs with the agendas in TOP management committees has shown that these paths are discussed particularly frequently. In addition, these paths are highly dynamic and the technical feasibility is usually not clarified during project initiation. From this it can be deduced that it makes sense to predict the *critical paths for project success*. The knowledge about critical paths can be used in the formation of the initial system of objectives (in the definition of product properties and functions) to model a *realistic, realizable product profile*. This means that it is not only in the late phase that it is determined that elements of the product profile cannot be implemented technically or economically.

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