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# Case study on prioritizing test cases and selecting the most qualified validation environment using an OEM's transmission application as an example

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## Abstract

Using the example of an Original Equipment Manufacturers (OEM) transmission application, it can be seen that large parts are currently being validated using real, physical prototype vehicles. Accordingly, validation in the automotive product development process (PDP) is taking place very late. In addition to this need for time optimization, another challenge is the complete validation of all variants of product generations in an OEM's product portfolio with, among other things, increasingly divergent, country-specific engine/transmission combinations. An advance shift of validation activities via simulation or test benches into the Early Phase in the Model of PGE – Product Generation Engineering can compensate these current disadvantages so that more extensive test cases can be mapped at an early stage. The selection of the validation environment is influenced by various factors such as the time in the PDP and the associated possible accuracy or restrictions due to limited or inaccurate representation of the environmental system. The knowledge gained from the specification or the variation of solution-open elements (e.g. product properties and functions) in the early phase of PGE allows early identification of critical subsystems. Nevertheless, there is a lack of systematic approaches that supports the product developer in choosing the most qualified validation environment depending on the variation shares. In the context of the paper, a case study is used to show that existing approaches have so far not been able to support the product developer with sufficient accuracy in choosing the most qualified validation environment. Furthermore, research gaps in the prioritization of test cases in the context of the PDP are identified. Finally, a first approach is presented on how existing methodological approaches can be further developed and merged to close the identified gaps.

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## 1. Introduction

Products are developed in generations - this is particularly evident in automotive development. The model of PGE - Product Generation Engineering is an explanatory model based on development methods that describe the emergence of new product generations through the activities of carryover and new development variation in practice [2]. In recent years, German Original Equipment Manufacturers (OEM) have improved approaches to efficient product development, such as the common parts strategy, kits and platforms. However, technical

feasibility and the holistic consideration of customer requirements can only be guaranteed by appropriate product validation. Product validation as a central activity - especially in the Early Phase of PGE - plays a key role in meeting customer requirements, generating knowledge and ultimately ensuring market success [3]. At the same time, activities for early validation on alternative validation environments are subject to special challenges resulting from a high degree of uncertainty. Nevertheless, inadequate validation activities in early phases can be associated with high costs for an automotive manufacturer in the late phase. Taking the example

of transmission applications, this means that in addition to the very restricted time window, test sites have to be rented, application engineers deployed and prototypes provided. This conflict can be solved by early identification and prioritization of test cases and their validation on qualified validation environments under consideration of the expected uncertainties

## 2. State of Research

### 2.1. Model of PGE – Product Generation Engineering

The model of PGE - Product Generation Engineering describes the creation of new products by two basic hypotheses [4, 2].

- 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 basis and starting point for the development of a new product
- The technical subsystems of a new product are developed based on reference system elements through the activities Carryover Variation (CV), Attribute (AV)/Embodiment (EV) and Principle Variation (PV).

The model of PGE can be used to explain phenomena of development practice, such as the production of prototypes in the Early Phase of PGE, which is made possible by a high share of carryover variation [5]. The Early Phase of PGE is defined as "a phase in the development process of a new product generation, which begins with the initiation of a project and ends with an evaluated technical solution, which finally 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 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. In particular, product development processes with a low percentage of carryovers show a higher development risk with regard to the technical issues [5]. The resulting test cases for reducing the development risk must be evaluated with respect to their criticality. An approach for evaluating the criticality of test cases is presented by Albers et al. with the criticality matrix, which takes into account not only the technology but also the influence on the overall system and the application scenario [6].

### 2.2. Reference Product Model

In the initial system of objectives, which was already introduced in the previous chapter, the first basic objectives for the development of a product are defined. The initial system of objectives is developed at the beginning of a product development process and continuously concretized [7, 8]. Product profiles support a holistic and systematic definition of objectives for a product generation. Product profiles are defined as: "[...] 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" [9]. Essential elements of the product profiles are objectives, requirements and boundary conditions of all relevant stakeholders as well as product characteristics, central functions and application scenarios of the product generation [9]. This strategic product identification with the help of product profiles is transformed into a reference product model according to Albers et al [1]. The model supports the concretization in a technical problem solving process from a solution-open to a solution-specific description of the product generations [10]. Basically, the model is divided into three views, which describe the properties, functions and technical subsystems (see Figure 1). Based on this classification, information of the reference product can be analyzed and abstracted. The most abstract view describes the product properties that are solution-open. According to Albers, product properties describe the characteristics of a technical product, which can be used to describe the behavior that can be experienced from the customer's or user's point of view [1].

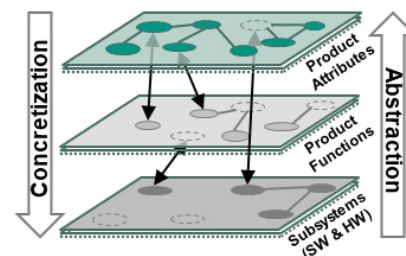


Figure 1: Reference Product Model [1]

The concretization of product properties can be done by product functions. A product function represents a function of a technical system, which describes a solution-open relationship of sub functions on a customer and/or user-oriented level [11]. Due to their higher level of detail, product functions can be interpreted as more solution-specific compared to product properties [1]. The highest degree of concretization is achieved at the level of the physical elements. Technical subsystems can be hardware as well as software components and serve to realize the required product properties and functions. With the help of product profiles as initial system of objectives, changes of relevant characteristics and functions can be identified at an early stage, which are realized by adapting the technical subsystems. Thus, it is possible to gain early knowledge about which adaptations are necessary on subsystem level.

### 2.3. IPEK-XiL-Approach

In the Early Phase of PGE the products to be developed are often only available as subsystems. Taking into account the demand for continuous validation, it follows that this must not only be carried out with the overall system, but already with the subsystems. However, in order to validate that the subsystem meets the requirements, the subsystem must interact with its overall system. The resulting integration of a subsystem into the virtual overall system is already established by the use of model, software and hardware-in-the-loop. Albers takes up these approaches in his IPEK-XiL-Approach and combines and extends their advantages [3, 12]. The "X" is to be understood

as the physical or virtual system that is in the focus of the current validation activity. The system to be validated can be available in different system levels (complete system or subsystem). This system is integrated into the environment, the overall system, and other interacting systems, such as the driver, and their interactions are mapped. In contrast to the classical approaches, the IPEK-XiL approach offers the advantage that the subsystems are not exclusively integrated into virtual environments. The type of interactions can thus be determined individually depending on the validation goal and can be purely virtual, purely physical or mixed physical-virtual. Depending on the validation objective, developers must, for reasons of efficiency, restrict the environment in its manifestation so that it represents only those parts relevant to the test cases and their results. This applies to all connected systems [3].

#### 2.4. Criteria for selecting a suitable validation environment

According to Albers a validation environment is a subset of the available validation system. According to the Integrated Product Development Model (iPeM), it comprises all developed elements (systems, methods and processes) that enable a validation of the product. [13] A validation environment is a concrete manifestation of the operation system for validation in relation to methods and the resource system for one or more combinations of a product, a point in the product life cycle and a validation goal [3]. Consequently, a suitable validation environment offers all prerequisites for validation activities according to the IPEK-XiL approach.

Due to the large number of possible validation environments, Yan presents a possible methodical approach for selecting the most suitable validation environment [14]. Starting from a validation goal of the product developer, basic requirements for the validation environment are derived, which also serve as exclusion criteria. This ensures that the defined validation goal can be achieved. In the next step, evaluation criteria are introduced, which, depending on their chosen weighting, are intended to support the selection of the most suitable validation environment. The evaluation criteria are assigned to four perspectives (technology, organization, user and economy). Besides the choice from existing validation environments, this approach also offers the possibility to develop and evaluate new validation environments (see Figure 2).

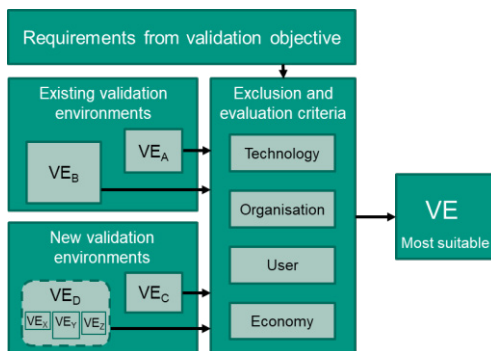


Figure 2: Methodical approach to select a suitable validation environment [13]

As YAN points out, the criteria listed do not claim to be complete. Furthermore, he already indicates that due to the

increasing system complexity of the products, consideration of the product properties can lead to an increase in efficiency for choosing the most suitable validation environment [14].

### 3. Case Study

In the following, the existing approaches from the state of the research are applied in a case study. The aim of the case study is to find out whether the approaches can be used to identify the most qualified validation environment in the context of the transmission application. The application of dual clutch transmissions of the Porsche 911 Carrera of the product generation 992 is used as a case study. By means of the analysis of the initial system of objectives, in the form of the product profile of the product generation 992, essential changes of the characteristics, functions and technical subsystems to the reference product (991.2) can be identified. Thus, it becomes clear that the technical subsystems engine and transmission are to be classified as embodiment variations, from which a direct influence on the function of the shift sequence can be derived. It can be assumed that the required property "shift quality", which is directly causally related to the function "shift sequence", should be at least at a similarly high level compared to the previous product generation. Due to the significant variation shares (EV Transmission; EV Engine), the fulfillment of the initial objective "shift quality" is connected with a high uncertainty from the point of view of the product developer. Taking into account the criticality matrix according to Albers, a moderate criticality results for the validation of the shifting quality and the test cases derived from it [6]. Although the influence on the overall system can be rated high, since drivability and thus the overall product perception is significantly influenced by the shift quality, the technology and application scenario are already known. The product developer can thus evaluate the technical uncertainties on the basis of the variation shares and determine the test case criticality by means of the criticality matrix. However, there is no systematic way to use this knowledge consequently, so that a temporal prioritization of test cases can be derived from it. A validation plan in the context of the PDP could be created on the basis of this systematic approach. With reference to the case study, an early validation of the test cases of the shift quality should be aimed at due to the high uncertainty based on the variation shares and the high influence on the overall system.

The earliest possible time for validation in the context of an OEM's transmission application is as soon as the basic engine and transmission application data is available. Only after this time is it possible to change gear including torque-overlap and speed-adjustment by the engine. Although the focus of application engineers at this point in time is still on basic functionality and not on shift quality, validation is still useful, taking into account the high degree of uncertainty regarding the fulfillment of the objective. Particularly bad or not feasible gear shifts can be identified at an early stage. This point in time in the PDP corresponds to about 2 years before Start-of-Production (SOP). Both engine and transmission are present as physical subsystems and the first Aggregate Carrier Vehicles (ACV) have been built. However, full-scale prototypes are not yet available at this time. Consequently, no validation

environment based on component availability needs to be excluded, since ACV can also be operated on full vehicle test benches or road tests. In order to be able to evaluate the shift quality by means of simulations, very complex and computationally intensive simulation models are required. Since physical elements are already available at this point in time, the simulation as a validation environment can be neglected for further consideration for reasons of efficiency and very high uncertainties regarding the model quality. For the evaluation of the most qualified validation environment, powertrain and full vehicle test bench as well as road test are therefore considered. The ability to exclude validation environments for evaluation, due to availability of parts or efficiency reasons at the given time, is not yet offered by the existing approach of Yan.

Taking into account the evaluation criteria according to Yan, it can be seen that the powertrain test bench is recommended at the given time (see Table 1). The evaluation as well as the weighting of the present criteria is based on an expert survey of the transmission application of Porsche AG. The weighting and the evaluation are strongly dependent on the individual experience of the developers and are therefore subjective. However, semi-objectivity can be achieved through standardization and direct comparison. As an example, only the criteria of technology and economic efficiency will be discussed more in detail below because of their high weighting. The technology is rated equally on both test benches, since a comparably high reproducibility can be expected, for example. This is not the case with road tests. In addition, the accessibility of measuring technology on the test bench, for example, is to be evaluated more positively. The powertrain test bench is the most economical of all validation environments, since the test bench costs are significantly lower than those of the full vehicle test bench. The road test is rated worst in this category, since in addition to the costs for the engineers, transport and travel costs as well as the test site are involved.

Table 1: Evaluation of the validation environments for the present test case (TFF - Target fulfillment factor; PUV - Partial utility value; Rating 0-5)

Criteria	Weighting	Powertrain test bench		Full vehicle test bench		Road test	
		TFF	PUV	TFF	PUV	TFF	PUV
Technology	0,35	4	1,4	4	1,4	2	0,7
Organization	0,15	2	0,3	4	0,6	2	0,3
User	0,15	2	0,3	2	0,3	4	0,6
Economy	0,35	4	1,4	3	1,05	2	0,7
Summary			3,4		3,35		2,3

In the context of the transmission application, however, selecting the validation environment on the basis of these four criteria is not sufficient, since none of the criteria takes into account the uncertainty of the expected result quality of the respective validation environment. In powertrain development, this uncertainty regarding the quality of the results describes the deviation of the results in comparison with the road test. It has already been discussed that the variation share of the physical elements, which have a direct influence on the shift quality (engine and transmission), is very high. However, since

these are already physically available and can be integrated into the validation environments to be evaluated, these variation shares can be neglected for the evaluation. However, for the powertrain test bench, in the context of the IPEK-XiL-Approach, the model of the residual vehicle (and all variation shares to the reference product) must also be reproduced. The expected uncertainty regarding the result is correspondingly high. This is not necessary for the full vehicle test bench as well as for road tests with ACV, since the physical model of the residual vehicle corresponds to the previous product generation. Only the powertrain (incl. engine and transmission) was adapted to the current development generation.

This means that if the residual vehicle model of the powertrain test bench is carried over from the predecessor product generation, the uncertainties regarding the result are comparable with those of the full vehicle test bench and road test at this specific point in time. However, if full-scale prototype vehicles are already available at the time under consideration, a completely different result of this analysis can be expected.

#### 4. Research Gap

Based on the case study, research gaps can be identified in the methodological support for prioritizing test cases and selecting the most qualified validation environments. These research gaps result, particularly in the context of the transmission application, in the fact that the selection of the most qualified validation environment cannot currently be described with sufficient accuracy. In addition, there is a lack of a consistent systematic approach to prioritizing test cases in terms of time within the PDP. The reference system model offers the possibility to identify necessary changes on subsystem level at an early stage in order to fulfill adapted product properties of the reference product. However, it is not yet shown how this knowledge base can be used systematically to derive critical test cases that need to be validated at an early stage. In addition, the product developer lacks decision support to choose the most qualified validation environment for these test cases. As shown in the case study, Yan already lists a selection of evaluation-relevant criteria for selecting the validation environment, but these are not sufficient in the context of the transmission application. It is evident, for example, that the uncertainties regarding the quality of the results of the validation environments are completely neglected. In addition, the planned time of the validation in the PDP and the associated availability of physical components and efficiency must be taken into account in the decision. Yan already gives an outlook that a consideration of product properties due to increasing system complexities can lead to an increase in efficiency of the methodological approach. It is particularly important to tie in with this point in order to support the decision-making process with knowledge already generated on the basis of the reference system model. In this context, knowledge about variation shares on the subsystem level can be particularly helpful in order to make estimates of the uncertainties to be expected.

## 5. Systematical approach

Based on the identified research gaps, the following chapter will outline how these can be addressed. This approach represents initial ideas, which will have to be specified and further developed in subsequent research.

### 5.1. Identification and prioritization of test cases

In the first step, the initial system of objectives, in the form of the product profile, is analyzed for early identification of changes in relevant functions and their essential influencing parameters. From this, essential changes for properties, functions and physical elements can be identified for the product generation. The next step is to identify conflicting goals that arise from the current planning status in the  $G_n$  product generation (see Figure 3). Conflicts of objectives arise in vehicle development depending on the functions to be implemented, such as launch control. Thus, in this function, the conflicts of objectives arise in particular in the interaction of the subsystems of the powertrain, the vehicle weight and the tire performance. Since these elements can be described relative to the direct predecessor product generation, the product developer can use the variation shares to estimate at an early stage what uncertainties will arise in order to meet the initial objectives.

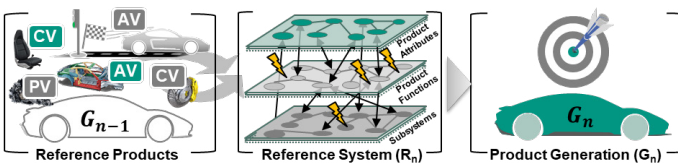


Figure 3: Identification of conflicting goals and uncertainties using reference system models

This knowledge should be used consistently to systematically derive test cases. However, an increase in efficiency can only be achieved if the derived test cases are prioritized in the context of the reference system. For example, test cases that are particularly uncertain with regard to the validation result (due to a high new development share of the varied subsystems involved) should be validated with a time prioritization, compared to test cases with a lower new development share and consequently a lower uncertainty. The temporal prioritization due to assumed uncertainties should additionally be considered in the context of test case criticality. Test cases that are particularly critical with regard to their relevance in the complete vehicle network (e.g. driving safety functions) must also be validated at an early stage. To evaluate the criticality of a test case, the criticality matrix according to Albers et al can be used [6]. Consequently, the temporal classification of the test cases spans a two-dimensional solution space depending on the variation shares and criticality.

### 5.2. Choosing the most qualified validation environment

Based on the identified test cases and their temporal prioritization in the context of the PDP, the next step is to support the product developer in choosing a qualified validation environment. Using the knowledge of the previous

chapter, the point in time in the PDP for the initial validation can be derived. From the time of the last possible product adaptation (often shortly before SOP), relevant test cases are assigned to the milestones (MS). Test cases with high criticality and a high proportion of variations should be validated at an early MS. By assigning the test cases to defined MS, it is possible to analyze the system availability of the physical elements at an early stage, since the availability of prototype vehicles, for example, is hard linked to the MS. With this knowledge, validation environments can be excluded from the selection process if necessary elements or components are not yet available at that time. Besides the time-dependent exclusion criteria, there are further exclusion criteria which result from physical boundary conditions. These can be used to ensure that the defined validation goal can be achieved with the present validation environment [14].

The remaining validation environments have to be evaluated in the next step. Yan is already introducing the criteria of technology, organization, users and economy, which will be taken up and expanded in the following. For this purpose, the knowledge about the variation shares from the reference system can be used again. In the context of the IPEK-XiL-Approach, the system to be validated is integrated into the overall system, the environment and all interacting systems. Therefore, with an increasing degree of abstraction of the validation environment, a higher risk with respect to its significance arises. The degree of abstraction is to be understood as a model of the residual vehicle model (see Figure 4). In late stages of the transmission development, the quality of the model and the associated significance of the validation environment can be determined by means of real driving tests.

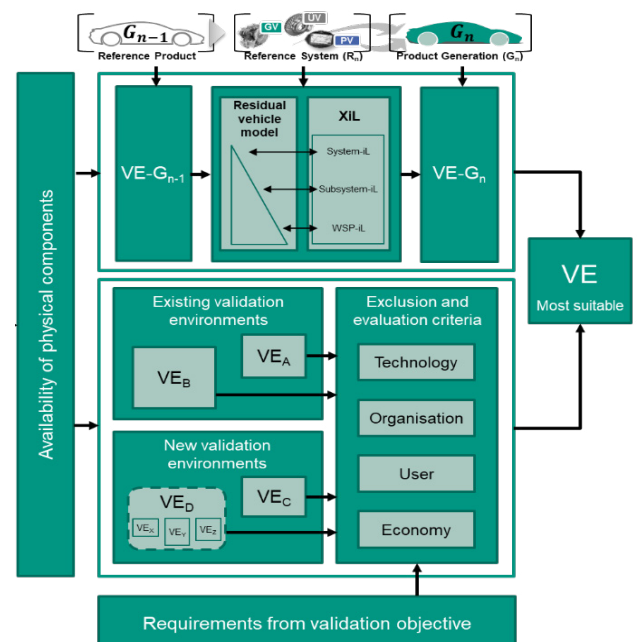


Figure 4: Basic Approach for choosing the most qualified validation environment

However, if no full-scale prototype vehicles are available, this is not possible, which is especially disadvantageous for simulations or powertrain test benches with a correspondingly high degree of abstraction. In order to be able to estimate the suitability of the validation environment for the present test case, the already generated knowledge of the variation shares

from the reference model can be used, since validation environments and their stored models are also developed in generations. The lower the proportion of variations of the subsystems or functions of the validating product generation, the lower is the necessary proportion of variation in the model of the validation environment. This correlation can be illustrated particularly impressively using the example of so-called facelift developments in the automotive industry. A facelift is a new product generation in which primarily exterior elements are changed. Accordingly, the proportion of carryover variations is high. This new product generation and its functions or subsystems can be validated on validation environments with a high degree of abstraction at an early stage, since the models of the validation environment based on the reference product are also adopted to a large extent. The confidence in the model quality and the resulting validation results is correspondingly high, without the need for a separate comparison with road tests. For the evaluation of the expected uncertainty, the classification system of Albers can be used (see Figure 5), which was initially developed for the estimation of a  $G_1$  product generation, but can be adapted depending on the context [15]. On the basis of this systematic approach, it is possible to consistently predict the level of confidence in the expected significance of the respective validation environment. Finally, this information should be placed in the context of Yan's weighted evaluation criteria, which provide a semi-objective recommendation on the choice of validation environment for a given test case. This results in a two-dimensional solution space in which the product developer should evaluate whether the expected uncertainty regarding the result of the recommended validation environment is acceptable for the present test case and time.

## 6. Discussion and Outlook

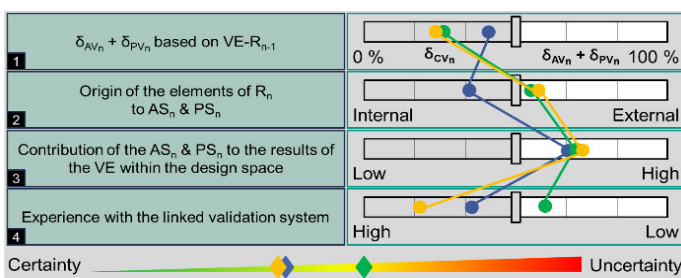


Figure 5: Classification system for evaluating the uncertainty of the results of the present validation environments [15] (blue - powertrain test bench; green - full vehicle test bench; orange - road test;  $\delta$  - Percentage of Variation Share;  $AS_n/PS_n$  - Quantity of subsystems in  $G_n$  that are developed by Attribute/Principle variation)

In the present work, existing approaches were used as part of a case study to first identify test cases to be validated in the PDP at an early stage and then to validate them in qualified validation environments. It became apparent that existing approaches in the context of the transmission application were not able to describe the associated requirements with sufficient accuracy. Based on the identified research gap, an approach was presented which, for the first time, uses knowledge about variation shares to earlier product generations to identify the qualified validation environment. This offers an enormous potential for early validation in terms of the frontloading

approach of the PDP. This approach has been developed for product generations within a product line. Whether and in what form the approach can be transferred to product generations of different product lines must be identified in further research.

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