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Objective based process model for enhancing the product maturity level in the early phase of a development process

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Abstract

In the early phase of a development process, several concept variations are developed to overcome technical problems. Despite this, only one concept makes the final selection. In this study, a theoretical process model providing an early-phase, structured proceeding guideline was adapted for use in a development process in order to simplify concept selection. This adapted process model enables a more time-efficient and transparent early-phase development process. Furthermore, it presents an opportunity for the relationship between design engineers and simulation engineers to be improved. The adapted process model was validated by using a combination of simulated models and expert interviews.

Keywords: requirements engineering; design process; design readiness level; maturity level; product enhancement; concept validation; early phase

1. Introduction and Motivation

The development process of a new vehicle generation can be influenced by changing constraints, such as new customer requirements or tightened legislation [1]. Facing these changing constraints unarmed may induce higher development costs. To minimize these costs, it is indispensable to pursue a straight development process and to be prepared to face changing constraints.

While developing a new car generation, the components of the car body undergo numerous changes. The car body is composed of many parts, which are connected by jointing technology. The car body functions as a basic framework and occupies an important role during the pursuit of development objectives, as it is developed further with each subsequent vehicle generation. The car body absorbs the forces that occur in a vehicle accident and thereby protects the occupants. Furthermore, the car body's contouring affects the vehicle design. Due to the high weight proportion of the car body on the complete vehicle, the vehicle weight can be reduced by using lightweight construction to improve vehicle performance. The product generation development by *Albers et al.* [2] states that the further developed car body of a new vehicle generation is always based on a reference system. This reference system can be the car body of the vehicle generation that has already been developed, or the car body of the vehicle of another automotive manufacturer. The reference system consists of elements which can be found in already existing products. Based on the reference system, the new product generation is developed. [3] The „[p]roduct generation development is understood to be the development of a new generation of technical products by both a specific carryover (CO) and new development of partial systems. The shapes of new technical developments of individual functional units result from the activity of shape variation (SV) and the variation of solution principles, hereinafter referred to as the activity of principle variation (PV)" [4]. As a carryover is caused by the regularly changing and increasing constraints

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during the development of a car body for a new vehicle generation, it is not an appropriate consideration for many car body areas. This leads to a high demand on shape variation and principle variation. In these areas, new structural components can be added, or existing structural components can be optimized to fulfill the requirements. To achieve this, the design engineer generates different design solution concepts. Based on the engineer's development experience, he selects the one concept that he considers the most likely to fulfill these requirements. The design engineer constructs this concept and passes it to the simulation department to simulate it in a virtual car accident. Simulation engineers must trust the experience of the design engineer, as he selects concepts that he considers most likely to achieve the objectives. The simulation results subsequently reveal the weak spots of the concept, which are analyzed by the design and simulation engineers. This analysis leads to two possible cases: In the first case, the concept is discarded as it does not fulfill the requirements meaning that a new concept must be developed which needs to be simulated and analyzed again. This case worsens the relationship between simulation and design engineers, since both must redo their work. In the second case, the design engineer needs to improve the shape by removing the weak spots. This also results in another run of simulation and analysis. The relationship between the simulation and design engineers may not be worsened in this case but a high time investment from the simulation engineers is required. In both cases, many iterations are needed to identify a concept which satisfies the overall requirements. Since simulations require high computational power, which customarily is not provided on local computers, they can only be performed at external computation centers, leading to rental charges. Considering the high amount of shape variations when developing the car body, it has an associated high simulation demand. This leads to a high utilization of the simulation department and increases the time effort of up to three weeks until the results can be analyzed. The design engineer is dependent on the simulation department to be able to analyze the nature of the model's weak spots. Furthermore, the relationship between design and simulation engineers can suffer from the fact that work may need to be redone after analyzing the weak spots several times.

There is the potential of reducing development cost and time by minimizing the dependency of the design engineer on the simulation department. Thus, the relationship and the trust between design and simulation engineers can be improved, if the design engineer is able to predict the best concept out of several. Therefore, a process model to methodically support the design engineer in the early phase was applied and evaluated in a case study. The case study took place in the context of the sports car car body development of the Dr. Ing. h.c. F. Porsche AG. The greatest challenge was to identify an opportunity for analyzing and evaluating design concepts, as the concepts must be evaluated at an earlier point in time than it is usually done. This means that the concepts' maturity at this time is very low because they are conventionally raised by passing through the iterations with the simulation department. Therefore, an opportunity must be identified to analyze and evaluate the concepts with a lower maturity level than during conventional development. The technical design problem for applying and evaluating the process model was the development of a hardtop structure for a sports car.

2. State of Art

2.1. The Early Phase of a Complex Product Development Process

The development of the hardtop structure of a new automotive generation starts with the generation of potential solution concepts for a technical problem. *Schwankl* [5] states, that during the early phase, there is the chance to have an impact on the whole development process [6,5]. The selection of a concept which will not achieve its objective affects the development process in a negative way, since it leads to more simulation iterations. By minimizing these iterations, time and money can be saved. However, deciding whether or not a concept will achieve its objectives is very difficult for the design engineer during this early phase [7] as a result of the lack of information on the product [5]. These concepts are depicted in a qualitative and informal way rather than in a quantitative and precise way [7] which leads to a non-transparent concept selection. Despite these insecurities, the design engineer must develop a design solution concept that can be proceed to serial development. Therefore, the design concept must have a high level of maturity, requiring no significant changes to the future concepts' shape. Following this, the concepts' maturity must be evaluated.

2.2. Process Models to Evaluate Maturity

A variety of different models exist to evaluate maturity; the most common being CMMI, SPICE and TRL. [8–10] All of these models are based on maturity stages, whereby a higher stage means a higher maturity. *Albers et al.* [11] describe the connection between the maturity level and the product generation development by „interpreting different degrees of maturity of prototypes as generations in development" [11,12]. Maturity degrees are also used by *Mankins* [9] in the Technology Readiness Level (TRL) that evaluates a technologies' maturity by using nine maturity stages. After having passed through all nine maturity stages, the technology has achieved the highest maturity level. [9] The application of existing models needs to be performed correctly. For example, the „[r]isk and cost of a development of a technology to a certain TRL level - that is suitable for introducing a product to the market - is an important element of a design process and needs to be evaluated and examined correctly. Applying mathematical operations on ordinal numbers of TRL creates incorrect estimations of the cost and risk of technology development as part of a design" [13]. This shows that existing models must be adapted when used in a development process.

To be able to evaluate a products' maturity, the product requirements must be defined, which is an aspect of requirements engineering. One main demand of requirements engineering is consistent documentation of requirements [14]. This documentation takes place in the system of objectives by *Albers* [15].

2.3. System of Objectives

The system of objectives contains all objectives, for example requirements, and their relations [15]. It contains the planned features of a product and is the central system in which all relevant information on a product is brought together. [15,16] Based on *Albers* [15], the „system of objectives describes not only the affordance and requirements of one single phase; the system of objectives is also linked to affordance and requirements of all other phases of the product life cycle“ [15]. Therefore, the system of objectives is important throughout the whole product life cycle. A complete and consistent modeling of a system of objectives can be made based on nine partial models [16]. The partial models are: function, shape, phases and product development activities, use cases, objectives, milestones and deliverables, requirements, tests and stakeholders [16]. The usage of a system of objectives is only expedient as long as it is consistently controlled whether the development process is correct and the actions of the development process are successful [17]. Therefore, it is essential to assign results to different milestones and consistently control whether the results have been achieved.

For modeling a system of objectives in the early phase, there is a theoretical process model which considers the product generation development process [2,18]. This theoretical process model focuses on the usage of reference system elements and provides a guideline for modeling objectives and selecting reference system elements. It shows which deliverables and sub-deliverables need to be achieved during the development process and how they can be achieved.

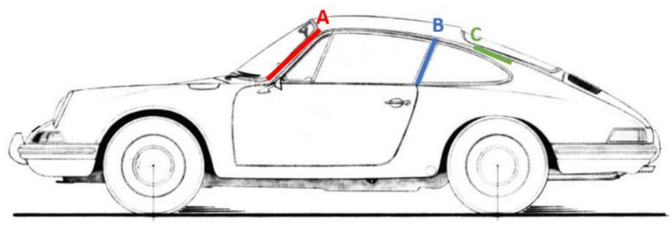
3. Research Method

3.1. Case and Research environment

The theoretical process model from Sec 2.3 was applied and evaluated in this case study in the context of the sports car body development and used to examine how and with which increment value it can be used for the development of a new car body. Consequently, a technical problem was chosen in the area of the hardtop of the new automotive generation. The hardtop protects the occupants in the case that the vehicle rolls over the hardtop in a car accident. To absorb the forces that occur in this case, the hardtop is connected to the rear part of the car body by a bracing structure. In this area a new bracing structure needed to be developed. This was necessary since the bracing structure of the former automotive generation did not fulfill the requirements in form of a carryover. The requirements were tightened by three factors:

1. The car body did not have a b pillar which absorbs a high amount of the forces in a car accident. Therefore, this amount needed to be absorbed by the a and c pillar. The car pillars are shown in Fig 1.
2. The engine was in the rear part of the vehicle which leads to a high amount of forces that need to be absorbed by the c pillar.
3. The distance between the heads of the occupants and the hardtop is very small. Thus, the resistance is minimized and the efficiency enhanced. In case of a car accident in which the car rolls over on the hardtop, the car body deforms due to the forces that occur. This deformation reduces the distance between the heads of the occupants and the hardtop. A contact must be prevented, which is why the bracing structure needs to fulfill very high stiffness requirements.

Fig 1. The three car pillars and their location in the vehicle [19].



3.2. Needs and Objectives for Research

There exist „necessary stages that each design problem needs to go through to transform to a product that can satisfy the customer needs” [20]. These design stages stretch from the inception of the ”design team(s) with required expertise” [20] to the product launch. In the conventional development process, a design engineer generates different solution concepts for a design problem. Until the final concept is identified, many iterations within the simulation department are needed. Each iteration requires time and development costs. Therefore, it is not possible to evaluate a high number of different concepts and concept variations. By using of the process model in this case study, a time- and cost-efficient concept evaluation should be enabled, which should be achieved by minimizing the dependency of the design engineer upon the simulation department. The design engineer must be able to perform evaluations that enable the selection of different concepts independently. During this evaluation, the transparency of the evaluation criteria should be raised in order to increase the comparability of the solution concepts.

The evaluation of concepts should be time-efficient but complete, otherwise a simulation could not be performed, and an evaluation could not be made. By evaluating the concepts at an earlier point in time they will not be as detailed, and the maturity will not less than in a conventional development. Therefore, an opportunity must be identified to guarantee the validity of the concept evaluation with a lower level of concept maturity.

By achieving these goals, the concept that fulfills the requirements the most should be identified at an early point in time, enabling the design engineer to use more development time to increase the maturity of the selected concept. At the end of the early phase, the concept maturity should be high enough that no further significant changes in the shape of the concept are necessary. The research questions were:

- How does the theoretical process model need to be adapted to be used in the process of product development?
- Can the adapted process model be integrated into a car body development process?
- Does the design solution concept developed using the adapted process model fulfill its requirements better than a reference concept?

3.3. Research Procedure

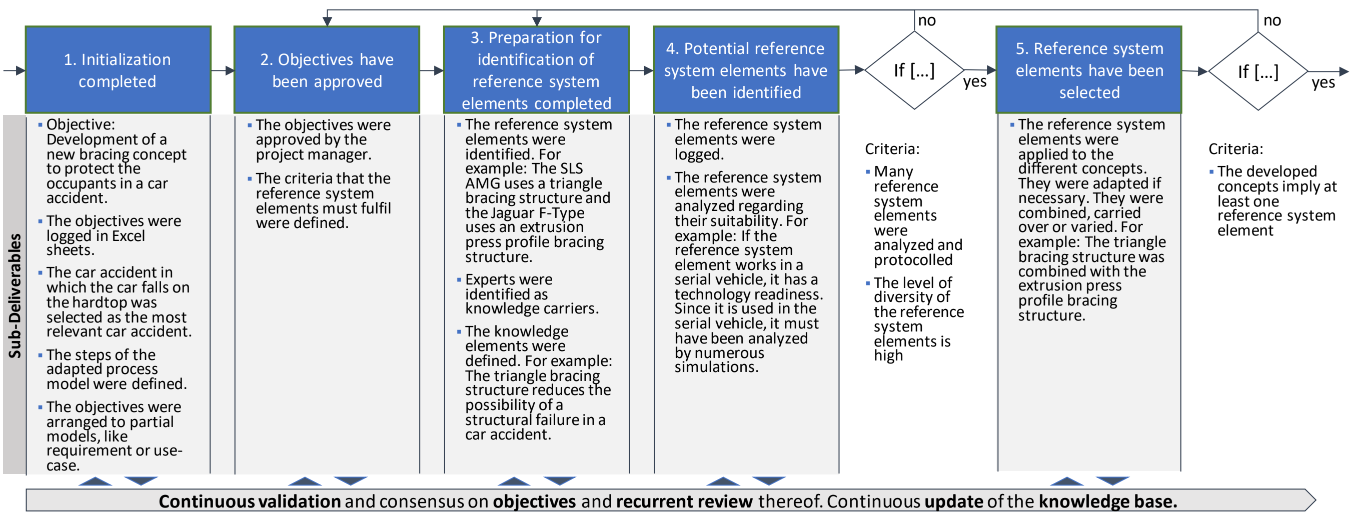
The theoretical process model described in Sec 2.3, was applied in the case study to validate its applicability and increment value. To be able to achieve an increment value via the theoretical process model, it first needed to be adapted. The resulting adapted process model is shown in Fig 2. The process model was divided into five steps with results that needed to be achieved after having finished each step:

1. Firstly, a simplified simulation model was established which did not require a high demand on computational power. Due to this simplification, it was ensured that the design engineer was not dependent on external resources. The simplified simulation model was an assembly of the components of the car body area in which the design solution concept should be integrated. In the case study, this area was the hardtop.
2. In the second step, solution concepts for a bracing structure were generated. These concepts were based on reference system elements which were identified by a benchmark analysis. The concepts were then integrated into the simplified simulation model.
3. In the third step, simulations were performed with the simplified simulation model and the concepts that were integrated into the simplified simulation model. These simulations showed the elastic performance of the hardtop in a car accident.
4. Based on the results of the simulation, the concepts were analyzed. Therefore, a level of objective achievement was introduced for analyzing and evaluating the concepts in a more transparent way. This level of objective achievement was based on a median value of the displacement of measuring points that were selected by experts. The interval of the level of objective achievement scale reached from zero to one hundred percent displacement value, with zero representing the maximum amount of displacement and one hundred representing no displacement. To be able to evaluate the level of objective achievement more transparently, a reference concept was constructed. This concept braced the hardtop right behind the seats of the occupants, comparable to a rollover cage, and achieved a level of objective achievement of 71,5%.
5. In the last step, the levels of objective achievement were compared and the concept which fulfills the requirements the most was selected.

Each step of the adapted process model and each result of these steps was validated by multiple experts. The adapted process model was validated based on whether the steps themselves and their application was clearly defined for the design engineer, and whether the design engineer can implement these steps in the development process. Subsequently, 24 expert interviews were performed within nine weeks with experts who define development objectives and design solutions to accomplish those objectives.

By using the adapted process model, the concept with the highest level of objective achievement was identified by the design engineer. This concept was compared to a technically inferior reference concept in further investigations. In these investigations, highly complex simulation models were built and compared to the simplified simulation models used by the design engineer. The reference concept which was compared to the new concept was one of the concepts that had a lower level of objective achievement. Both concepts were simulated on external computation centers. The simulation results were compared in three critical points of the car body by simulation experts. The first point was in the area where the bracing concept was located. If a high rate of deformation is present in this area, the hardtop structure could fail in a car accident. The second and the third point were located above the heads of the occupants. A high deformation in this area could lead to a contact between the hardtop and the heads of the occupants.

Fig. 2. Allocation of the five process steps from the adapted process model, based on the visualization of *Richter et al.* [18]



4. Results

4.1. Adapted Process Model Used in the Case Study

In this section, the adapted process model that was used in the case study is presented. Every step of the adapted process model was allocated to the corresponding steps of the theoretical process model from Sec 2.3. This achieved the objective to validate the possibility of using the theoretical process model in the development process of a new automotive generation. For the first time, the theoretical process model [18] was used in terms of an adapted process model in an industrial development process. Each step of the adapted process model was validated by experts. Furthermore, a complex simulation model was built to validate the veracity of the highly simplified simulation model as well as the steps of the adapted process model.

4.2. Validation of the Adapted Process Model

The steps of the adapted process model were evaluated by experts. The first question was whether the steps of the adapted process model and how to apply them were clearly defined for the design engineer. The second question was whether the design engineer could implement the steps in the development process.

The results of the expert interviews are shown in table 1. Both questions were answered by each expert regarding their level of agreement. The scale started at one, which means that the expert does not agree, to five, which means that the expert fully agrees. Hereby, each of the five process steps were taken into consideration. For each process step, the average from the expert answers was calculated. If the average value is greater than or equal to four, the agreement of all experts was sufficient. This was the case for both questions in each single process step.

Table 1. Validation of the process steps by experts of the car body development and the simulation department.

Process Step (PS) ↓	Question 1					Question 2				
	Are the steps of the adapted process model and how to apply them clearly defined for the design engineer?					Can the design engineer implement the steps in the development process?				
	Scale from 1 (no agreement) to 5 (full agreement)					Scale from 1 (no agreement) to 5 (full agreement)				
	Expert (E)					Expert (E)				
	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5
PS 1	4	3	5	5	5	5	3	4	5	5
Ø			**4,4**					**4,4**		
PS 2	4	4	4	5	4	5	4	4	4	4
Ø			**4,2**					**4,2**		
PS 3	4	4	5	4	4	4	4	3	5	4
Ø			**4,2**					**4**		
PS 4	4	3	5	5	5	4	4	4	4	4
Ø			**4,4**					**4**		
PS 5	4	3	5	5	5	4	4	4	4	4
Ø			**4,4**					**4**		

At this point, the five process steps of the adapted process model were evaluated by experts. Subsequently, the results of the five process steps of the adapted process model were evaluated by the same experts. The first question was whether the results of the steps of the adapted process model were clearly defined for the design engineer. The second question was whether the design engineer could implement the results of the steps of the adapted process model in the development process.

The scale for the level of agreement of the experts was equal to the scale used in the previous expert questioning: The value means no agreement and value five means full agreement of the expert. For both questions and each result of the process steps, the average value for the level of agreement was greater than four.

Table 2. Validation of the results of the process steps by experts of the car body development and the simulation department.

Process Step (PS)	Question 1					Question 2				
	Are the results of the steps of the adapted process model clearly defined for the design engineer?					Can the design engineer implement the results of the steps of the adapted process model in the development process?				
	Scale from 1 (no agreement) to 5 (full agreement)					Scale from 1 (no agreement) to 5 (full agreement)				
	Expert (E)					**Expert (E)**				
↓	E1	E2	E3	E4	E5	E1	E2	E3	E4	E5
PS 1	4	5	5	4	5	4	4	4	4	4
Ø			**4,6**					**4**		
PS 2	4	4	5	5	4	4	4	5	5	5
Ø			**4,4**					**4,6**		
PS 3	4	4	5	5	5	4	3	5	5	4
Ø			**4,6**					**4,2**		
PS 4	3	3	5	4	5	4	4	5	5	4
Ø			**4**					**4,4**		
PS 5	5	5	5	5	5	5	5	5	5	5
Ø			**5**					**5**		

In both surveys, all average results for each process step were greater than four. Therefore, the validation of every question was rated as successful.

4.3. Simulation based investigations on the developed concept

By the interviews shown in Sec 4.2, the adapted process model was analyzed and validated by experts. To verify that using the adapted process model leads to better development results, further investigations were made using models and simulation tools. These further investigations were performed on the concept that was identified by the usage of the adapted process model as well as on a reference concept. Therefore, a complex simulation model was built by simulation engineers. By using the results of the simulations, the newly developed concept was compared to a reference concept. For this comparison, three critical displacement points were identified and analyzed by experts. The results of this comparison between the simulation results by three simulation experts are shown in table three and four.

Table 3. Comparison of the new developed concept with a reference concept by experts in three critical displacement points.

		Expert (E)		
		E1	E2	E3
Question		**Does the new concept deform less than the reference concept in the following three critical displacement points?**		
Critical displacement point	1	Yes	Yes	Yes
	2	Yes	Yes	Yes
	3	Yes	Yes	Yes

Table 4. Comparison of the new developed concept with a reference concept by experts.

	Expert (E)		
	E1	E2	E3
Question 1	**Do you rate the improvement of the new concept as "high" compared to the reference concept? If the answer is „yes", why?**		
Answer	Yes, because only the new concept fulfills the requirements in a car accident.	Yes, because only the new concept could prevent a structural failure.	Yes, because the less deforming new concept protects the occupants.
Question 2	**How can you validate the answer from the previous question?**		
Answer	If the distance between the hardtop and the heads of the occupants is too low during a car accident, the concept does not fulfil the requirements.	The simulation results of the reference concept show the beginning of a structural failure.	If the displacement of the critical points is too high, the hardtop and the heads of the occupants could contact.

The comparison between the new concept and the reference concept showed the improvement of security for passengers in a car accident regarding the new concept. The improvement was rated as high by all experts. The new developed concept, which was developed by using the adapted process model, protected the occupants more successfully than the reference concept. The reference concept was developed without using the adapted process model.

5. Discussion

The validation of the adapted process models by experts proved that the theoretical process model can be used for the improvement of the development process by transferring it into an adapted process model. The identification of one concept that has the highest level of fulfilling the requirements was realized in a time-efficient way. The validity of this identification was approved by using simulation models and analyzing the results with simulation experts. This leads to the conclusion that the application of the adapted process model can potentially reduce development time in the early phase that can be used by the design engineer to raise the maturity level of the final selected concept.

6. Conclusion and Recommendations

The adapted process model enables an economic and time-efficient concept validation for the design engineer in the early phase of a product development process. Furthermore, the design engineer is now able to do a pre-selection between different concepts themselves. Therefore, the likeliness that they pass a concept to the simulation engineers that does not fulfill the requirements is minimized and the trust relationship between design and simulation engineers can be improved.

In further studies, the adapted process model should be used in different environments other than sports car body development. By doing this, it would become evident which adaptions need to be made to the process model to use it in a different environment of product development.

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