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VALIDATION OF PRODUCT PROPERTIES CONSIDERING A HIGH VARIETY OF COMPLEX PRODUCTS

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1. Introduction

Manufacturing technical products requires complex design processes as well as complex product architectures. One important aspect is the validation process for technical products. The authors' view on validation is the identification of appropriate dimensioning of components' characteristics. This dimensioning must consider typical and critical applications of the product. Consequently, poor validation methods lead to low product reliability and functions over engineering which in turn lead to a loss of profit.

Today, the validation processes for complex products are also becoming more and more complex. The reasons for this are manifold: there is increased product variety caused by the increasing complexity of the customers' requirements, and the increased technical capabilities of the original equipment manufacturer (OEM); furthermore, the integration of multiple domains within one product, such as mechanics, software, electronics and service [Lindemann 2006] leads to complex validation processes.

Increasing time and cost pressures are forcing OEMs to streamline their validation processes. Although OEMs must assure the properties of the whole range of products, they only have the capacity to analyze a small subset. One alternative is to develop methods that use the results from a test set to validate the properties of the whole range of products [George 2005], [Klein 2007]. In addition, the validation processes as well as the whole process of developing a product rely on the experience gathered from developing previous projects [Lindemann 2006]. Thus the validation methods must take modifications and future trends into account.

Between 60% and 80% of the components used in complex products by OEMs are subcontracted [Rezayat 2000]. Usually, suppliers provide several variants for some of these components, with diverse characteristics and properties. During the design processes, the OEM determines the components' characteristics with consideration for the required properties. The authors' approach involves assessing the product's properties in order to validate the design goals. Therefore the authors analyzed the application of the complete product and its components.

Two key factors affect the components' properties. On the one hand there is the application of the complex product (e.g. different environmental temperatures or diverse performance requirements), and on the other there are the characteristics of the used components (e.g. material). Hence the product's properties are closely linked with the components' characteristics and the functions they are fulfilling.

However, there is no systematic approach to evaluate product properties with consideration for these two main factors. This paper presents an approach to help evaluate product properties according to the product's application and the components' characteristics. This evaluation builds the basis for the validation. The paper is structured as follows: After defining relevant terms in section 2, a short review of current validation methods and the author's focus is presented in section 3. Section 4 presents a procedure model to support the validation of product properties, taking a large variety of products into account. The approach is demonstrated through an evaluation of a car's power consumption in section 5. Finally, the paper discusses possible next steps.

2. Definitions and examples

In order to support a general understanding, this chapter presents some short definitions of the fundamental terms. Figure 1 and Figure 2 depict the most important relationships between the terms used. Figure 2 depicts the connections between product's components and how their properties impact the composed property. Figure 1 depicts various components. Each of the components has several dimensions according to the components' characteristics. Hence the product variety can be very high.

2.1 Properties and characteristics

Product properties and characteristics in this definition are distinguished according to [Andreasen 1980]. He refers to characteristics as those product parameters that are directly manipulable by the engineer (form, structure, etc.) and defines properties as the performance of the product (function, safety, aesthetics, costs, etc.) that is only indirectly manipulable by the engineer.

2.2 Complex product

A complex product's numerous components and their interactions form a system. Such a system possesses individual properties that contribute to fulfilling the product's purpose, according to the system's definition by [Boardman 2005]. Examples of complex products are cars or aircraft.

2.3 Component

A component is a part of the complex product. Each component fulfills one or more subfunctions of the complex product. Between 60% and 80% of the components that OEMs use in complex products are subcontracted. Suppliers provide various dimensions for some of their components with diverse characteristics and properties.

2.4 Variant

A variant is one specific complex product. Two variants differ in at least one characteristic of one or more components.

2.5 Product variety

The product variety defines the whole range of variants provided by the OEMs to the customers (see Figure 1).

Components	Components' Dimension (Option)		
Component A	C–A, 1	C–A, 2	C – A, 3
Component B	C–B, 1	C–B, 2	C – B, 3
Component C	C–C, 1	C–C, 2	C – C, 3
...	...	...	

Product Variety = Variant 1 + Variant 2 + ... + Variant n

Figure 1. Product variety

2.6 Composed property

The composed property of a complex product originates from the concurrence of the components' property during the application of the product (see Figure 2). The manner of concurrence itself depends on the property. Whereas the product's composed property *weight* accumulates the weights of all involved components, the proposed property *sensitivity* is defined by the component with the highest sensitivity.

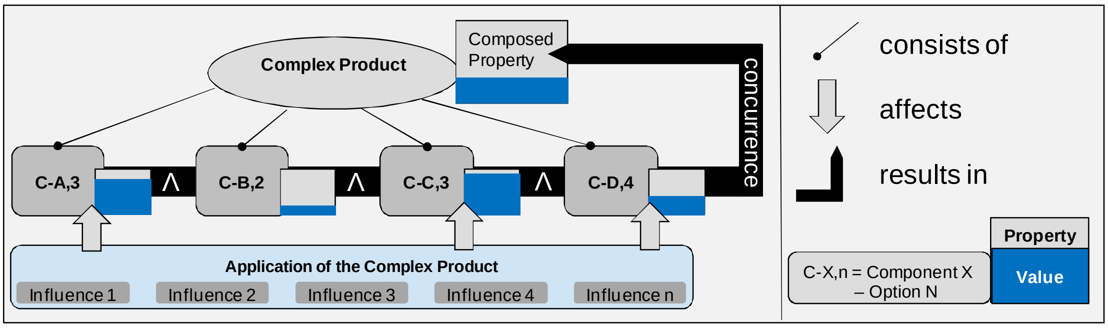

Figure 2. Composed property

2.7 Validation

The authors' view on validation processes involves comparing the product's properties' values with design goals. The validation processes use data from the development of previous projects wherever possible. Thus the validation methods must take modifications and future trends into account. The outcome of the validation processes is used in order to derive the dimensioning of parts, e.g. components of the complex products. For example, the proposed property *sensitivity* of a complex product must be evaluated in order to derive the performance of protective components.

3. Current use of validation methods & focus of this paper

Validation processes are becoming more and more complex. Due to rising technical capabilities and a wide variety of customer requirements, OEMs are increasing their product variety in order to increase profits [Firchau 2002]. According to the various characteristics of subcontracted components involved in complex products, the product variety can be very high. While the characteristics of each subcontracted component are well known, the impacts of the involved components on the composed product variety during the product's application are difficult to predict [Lindemann 2009] (see Figure 2). The frequency and manner of the components' application are controlled by the functions they fulfill. The product functions depend on various influences within the product's application.

In order to consider this, one validation approach is to execute product tests [Schwankl 2002]. Performing product tests requires knowledge about typical application scenarios for the product. Extreme application scenarios are also beneficial in order to validate product properties [Lindemann 2006], [Schwankl 2002].

Increasing time and cost pressures are forcing OEMs to streamline their development processes [Lindemann 2006]. Because of the large product variety for some products, one approach is to perform product tests with a small subset of the product variety [George 2005], [Klein 2007]. Accordingly, the validation methods must use the analysis results in order to derive properties for the remaining variants. This requires knowledge about the application's impact on the components' properties on the one hand, as well as knowledge about its impact on the composed product property on the other. The required information can be gained by analyzing and interpreting product tests.

During the validation procedure using product tests with consideration for high variety, several subproblems occur that must be considered.

First, prior to the execution of product tests and evaluations, basic dependencies between the influencing factors, product functions and components must be identified [George 2005], [Klein 2007]. Knowledge about their main impacts on the product's functions and components supports the design and evaluation of experiments. Structural complexity management (SCM) methods can be used to obtain transparency and to derive a better understanding of the complex product [Lindemann 2009]. Experience gained from previous projects provides additional input for subsequent subproblems.

Next, proper test sets, test setups and test processes can be derived using design of experiments (DoE) methods; in particular, Taguchi's and Shainin's methods are applicable [George 2005], [Klein 2007].

The next step is evaluating the test results. Here, a variety of analytical methods can be applied in order to identify the dependencies between the product's application, the components' properties and the composed property. The analysis of variances [George 2005] and correlation analysis are

particularly helpful in the first stages of the evaluation process [Ford 2005]. Regression analysis can be applied in order to quantify dependencies.
Next, the product variety must be considered. As a result, additional methods for adapting the test results must be applied. Finally, the transfer of the test results from existing components to future components must be considered. In order to identify change impacts, SCM can be applied [Lindemann 2009].
To conclude: There are various methods available to support the subproblems that must be considered when evaluating product properties. In particular, a high product variety leads to complex problems. However, there is no systematic approach that contains methods for the subproblems described above. Consequently, poor validation methods lead to low product reliability and functions over engineering. Both impacts lead to a loss of profit [Kececioglu 1991]. The objective of the author's approach is the dimensioning of the parts, e.g. components of complex products. This dimensioning considers typical and critical applications of the product.

4. Supporting the validation process for complex products

This section presents the authors' procedure model to support the validation process for complex products as described above (see Figure 3). It contains 5 phases. All of the phases contain methods to provide information that must be considered during the validation process of complex products. The execution of the first, third and fourth phase depends on the availability of project data from preceding products. According to the changes and advancements from series to series, each of the methods proposed in these phases can be beneficial. Figure 3 assigns the applied methods and expected results to each phase of the procedure model. As this paper is focused on identifying dependencies between the product's properties and the product's application, in the following passages the second, third and fourth phases of the procedure model are described in more detail.

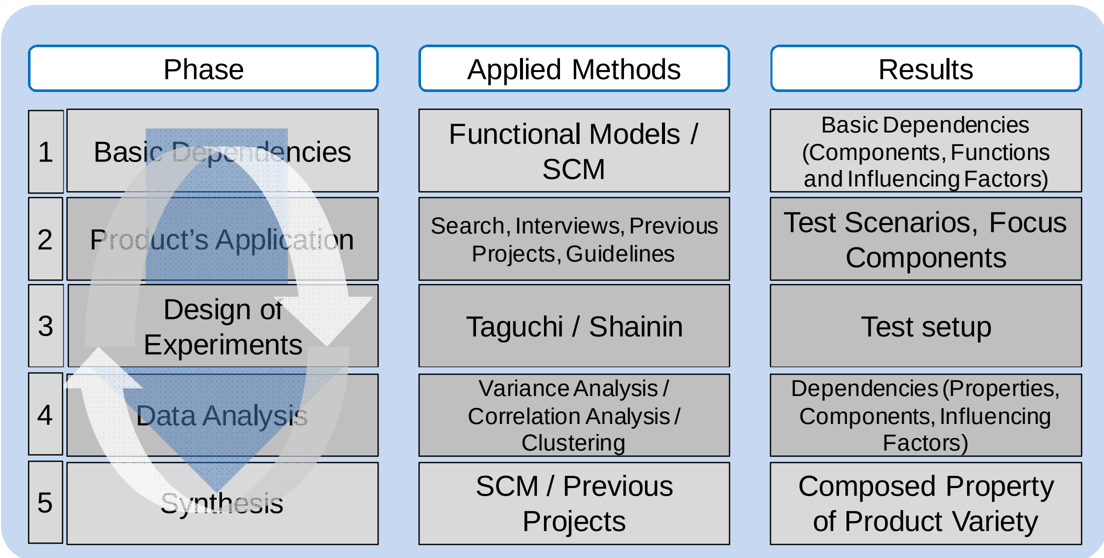

Figure 3. Procedure model supporting validation for complex products

4.1 Identification of basic dependencies

The first phase focuses on identifying basic dependencies between the components of the product, their properties and the product's application. First of all, the validation's composed property must be defined, and the way in which the single component properties are related to it must be clarified (e.g. the minimum sensitivity or the sum of the weight). Function modeling is used in order to identify the relations between product properties. SCM methods are also helpful here for structuring and analyzing the respective relations. The application of the product must be considered in order to identify critical factors that highly influence the components' properties. This helps identify highly fluctuating components. Input from previous projects can be used to adjust and justifying the dependencies.

4.2 Identification of a product's application

In this phase, the typical and extreme applications of the product are identified on the basis of interviews, previous projects, guidelines and standardized regulations. The distribution of the individual phases during the application must be determined, and the influence of each phase on the product's properties must be analyzed. Especially when it comes to analyzing the influence of the application on the product's property, pre-existing data can be helpful. In combination with the basic dependencies from phase 1, this phase identifies the focus components that are most important for the further validation.

4.3 Design of experiments

During this phase of the procedure model the product variety and the quantification of the influencing factors (identified in the first phases) is addressed. As described in the introduction, only small subsets of the whole range of products can be considered in order to keep the level of effort low. Choosing the right products within this subset is crucial for the validation of the complete product variety. Existing methods from the field of Design of Experiments can be applied here. For example, similarities between the variants or certain characteristics of the components can be used when choosing appropriate subsets. Then, promising combinations of important influencing factors and variants can be arranged in several experiments. The result of this phase is the test setup, where both the subset and the sequence of tests are defined.

4.4 Performing data analysis

Data analyses are performed in this phase in order to identify the dependencies between properties, components and influencing factors. If data from previous analyses is already available, it should be used for the analysis. If no data exists, initial tests are performed in order to gain an impression of the influencing factors during the application. The factors with the greatest influence must be isolated and varied during the tests. Again, methods from the Design of Experiments can be applied here to create an intelligent variation or a combination of influence factors.

The pre-existing or newly gained data is used within various analysis methods. First of all, variance analysis of data sets from different tests can be used to identify or confirm focus components. Correlation analysis is used to identify dependencies between influencing factors from the application and component properties. Clustering algorithms can serve to highlight groups of influences here.

4.5 Synthesis of composed property

In the last phase, the results from the previous steps are aggregated. First of all, the results of the data analysis are compared with the initial basic dependencies, and the identified dependencies are quantified if possible. In order to determine the composed properties of the entire range of products, the properties of the identified subsets must be transferred. The information from phase 1 (basic dependencies) and phase 4 (influencing factors) are combined, and the respective properties are derived.

5. Industrial application

In the following passages, the procedure model is applied. To do so, the authors analyzed several electrified components of a car's drive train. The analyzed property is the power consumption of the components involved. The objective of the project is to validate design goals, particularly the dimensioning of involved components. In doing so, the authors analyzed test data from previous-generation test results. The subsequent data describes a small section of the complete data. It is anonymized and manipulated in order to prevent reasoning based on technical implementation.

5.1 Identification of basic dependencies

First, the authors analyzed the property of *power consumption*. The composed power consumption of the drive train can be calculated by summing up the power consumption of the components involved.

Thus the largest impact on the composed power consumption is provided by components with high power consumption. These components are defined as focus components.

Functional models help the authors identify four groups of electrified components. The first group contains components with constant power consumption, such as sensors. In terms of the validation of design goals, this group provides no challenges. The second group contains components with constant power consumption that depends on the component's characteristics. This group assumes knowledge about the component's characteristics. The third group contains components with power consumption that depends on the product application, such as fuel pumps. Finally, the power consumption of the fourth group's components depends on both of the key influence factors (application and characteristics), such as fans. Thus the authors focused on components in the third and fourth group in order to derive the dependencies between the key factors and power consumption. The power consumptions of the first and second group's components can be determined without analyzing the whole car.

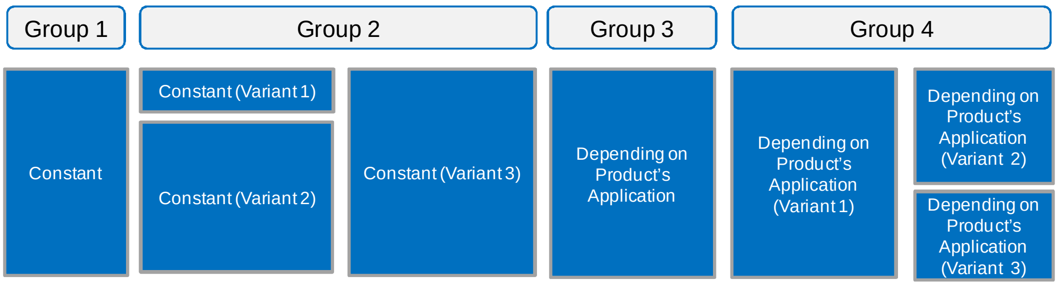

Figure 4. Identified groups with varying key influence factors

Based on the main functions of the car's drive train, the authors combined functional models, components and influencing factors. SCM can be used to deduce indirect dependencies (such as influencing factors that impact functions fulfilled by components). These influence models (example shown in Figure 5) provide initial information about the most important influencing factors. The authors used this knowledge in order to derive initial assumptions about components with varying levels of power consumption.

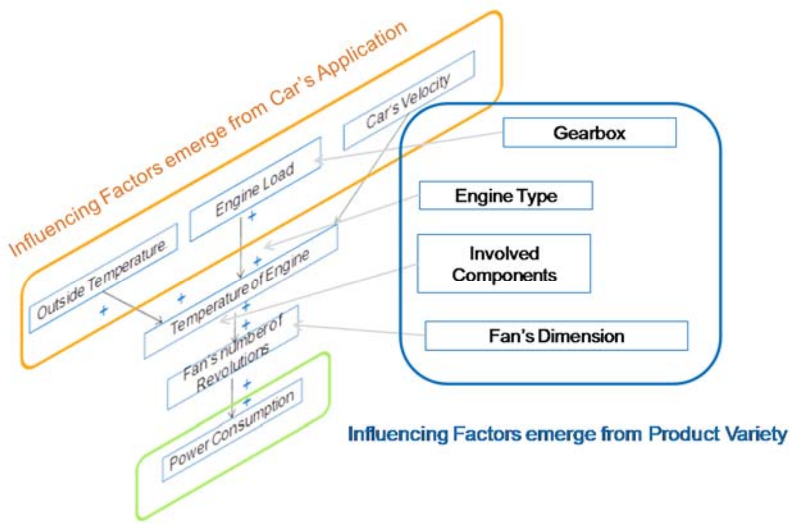

Figure 5. Simplified influence model of a fan (group 4)

5.2 Identification of the product's application

This phase analyzes the application for a car. Typical and extreme use cases and scenarios derived by way of interviews, guidelines and previous projects provide useful information. In order to derive fuel consumption and additional data, cars are tested using driving cycles. OEMs typically use different driving cycles with several variations of influencing factors (velocity, outside temperature, acceleration phase, etc.). In order to derive the influence of the focus components' power consumption on the composed consumption of the drive train, driving cycles can be decomposed into different phases (depicted in Figure 6). Next, the mapping between functions, components and influencing factors (basic dependencies) can be used to derive a weighting. The weighting indicates the most influential and critical components.

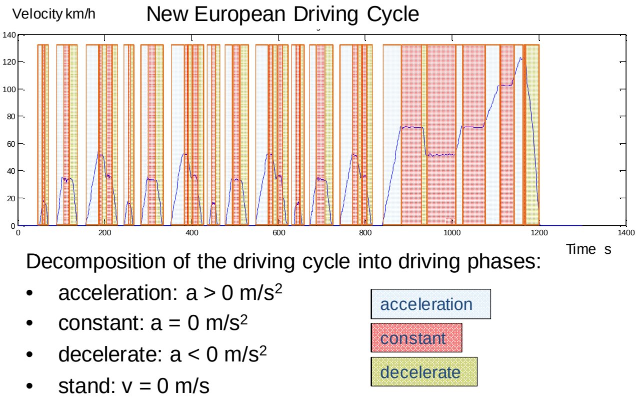

Figure 6. Decomposition of a driving cycle

5.3 Design of experiments

The authors analyzed data from previous-generation test results of the car's drive train. Hence the authors did not focus on which variant was appropriate to derive dependencies between the car's application and the power consumption of the car's drive train. The authors identified two groups: the components involved in drive trains of gasoline engines, and those in the drive trains of diesel engines. According to this distinction, most of the subsequent analyses will be performed separately. The data from previous-generation test results include promising combinations of the most important influencing factors.

5.4 Performing data analysis

In this step, the authors used data from previous projects to derive the power consumption of the focus components and associated influencing factors. First, the authors confirmed the TOP-10 components with consideration for several driving cycles and several variants. To do so, the authors calculated the mean power consumption (within all tested driving cycles) for all focus components. Additionally, the authors calculated the mean power consumption values with consideration for all mean values for each focus component. Then the authors performed a variance analysis with consideration for the calculated mean values for each focus component. According to the validation of power consumption, the authors identified a criterion describing the criticality of a component. On the one hand, components with high mean values have a high impact on the composed power consumption. On the other hand, the power consumption of components with high variance is difficult to predict. Therefore the criticality criterion (mean value * variance) is reasonable (see Table 1).

Table 1. Criticality of focused components (considering variants and driving cycles)

Component	Unit	Mean	Variance	# Values	Criticality
Component 1	[A]	7,24	8,08	17,00	58,53
Component 2	[A]	2,60	13,30	17,00	34,54
Component 3	[A]	1,04	4,99	17,00	5,21
Component 4	[A]	2,59	1,24	25,00	3,21
Component 6	[A]	2,23	1,10	10,00	2,45
Component 5	[A]	4,22	0,50	11,00	2,11
Component 7	[A]	2,75	0,34	17,00	0,94
Component 8	[A]	1,59	0,10	11,00	0,16
Component 9	[A]	0,22	0,30	11,00	0,07
Component 10	[A]	0,31	0,11	5,00	0,03

In the next step, the authors analyzed the criticality of the same components with consideration for different driving phases. For this purpose, the authors calculated power consumption variances within one driving cycle for each focus component. The outcome of these analyses is knowledge about the focus components and their criticality in terms of product variety as well as their criticality in terms of the product's application.
Next, the authors moved on to identifying the influencing factors with consideration for the product's application. In order to create a preselection, the authors performed a correlation analysis. To do so, the authors calculated correlation coefficients r_{xy} for all of the data streams (see Table 1). More precisely, the consumption values for each component within one driving cycle form one stream of data. In addition to the streams of the focus components, additional streams of data that considered the potential influencing factors (such as velocity, number of revolutions, actual gear, acceleration) were analyzed. Next, the authors modeled a dependency (see Figure 7) between two streams of data, if calculated correlation coefficients r_{xy} >0.7. For this purpose, the authors used a Design Structure Matrix (DSM) to illustrate the dependencies between the component's power consumption and influencing factors. Moreover, the authors applied a cluster analysis in order to derive possible dependency cluster.

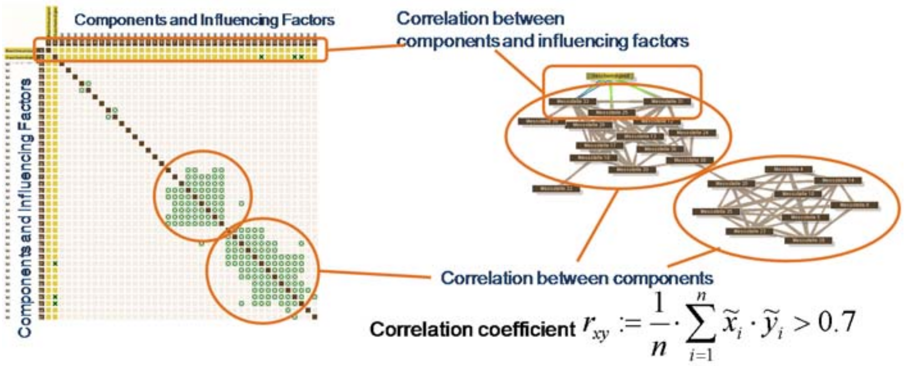

Figure 7. Clustered correlations between components and influencing factors

This way, the authors were able to identify several potential impacting factors. Finally, the authors performed detailed analyses of the dependencies between the identified impacting factors and the component's power consumption. For this purpose, the authors used the potential dependencies derived by way of the correlation analysis. In order to confirm and to quantify the dependencies in detail, the authors analyzed several streams of data, taking the previous steps into consideration. Hence the mean values, criticality values and potential influencing factors are considered. To do so, the authors checked dependencies between the streams of data and time (see Figure 8). In this case, the consumption for component 5 is constant. Component 5 performs a kind of warming phase that differs for different engines. The consumption for some components depends on the number of revolutions, e.g. for component 2. In this case, the power consumption varies for different engines, but the behavior is the same.

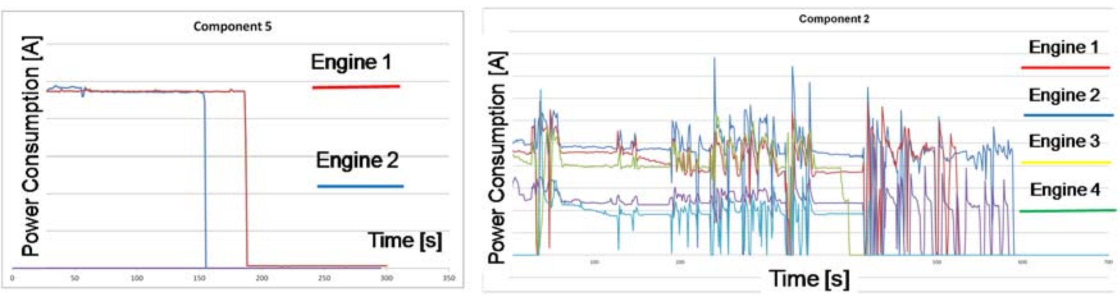

Figure 8. Time dependency (left) and revolution dependency (right)

Figure 9 (left) demonstrates the influence of outside temperature on component 3. In this case, the behavior is not the same. Figure 9 (right) depicts the dependency between component 4, velocity and engine load.

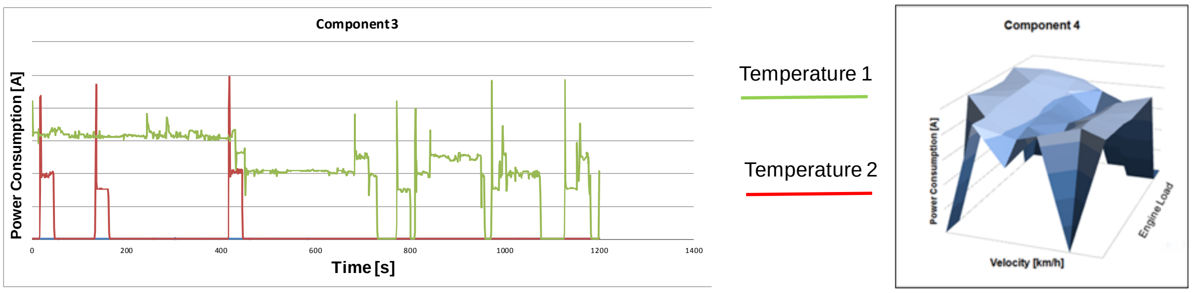

Figure 9. Dependencies between component 3 and temperature (left), dependencies between component, velocity and engine load (right)

These analysis results are aggregated to create an influence model (see Table 2). This model contains the dependencies between identified influencing factors and the power consumption of the focus components. Value 9 indicates a high influence, value 3 a mean influence and value 1 a small influence. This model considers influences for different variants by calculating mean influences. In future work DoE methods will be used in order to quantify the influencing factors.

Table 2. Small section of the identified dependencies

Component	Mean [A]	Variance	Criticality	Temperature			Velocity			# Revolutions			Engine Load		
				high	media	low	high	media	low	high	media	low	high	media	low
Component 1	7,24	8,08	58,53			9		3	9				9	3	
Component 2	2,60	13,30	34,54	9	3	1				9	3	1			
Component 3	1,04	4,99	5,21	9	3			3	9				9		
Component 4	2,59	1,24	3,21				3	1					9	3	
Component 6	2,23	1,10	2,45							9	3				
Component 7	2,75	0,34	0,94										3	1	

5.5 Synthesis of composed property (outlook)

In the last phase, the results from the previous steps are aggregated. First of all, the results of the data analysis are compared with the initial basic dependencies and the identified dependencies. For this purpose, the authors use standard consumption values for each of the focus components. The average usage of the involved components can be calculated according to the weighting of driving phases in typical driving cycles.

The consumption for several variants of the same component varies, whereas the behavior of different variants can be similar (see Figure 8). These similarities can be used in order to transfer the results to further (untested) variants. To take future developments and trends into account, the derived dependencies can be used as well.

Finally, the composed property of each variant can be identified. To do so, the consumption values of the focus components must be summed up. Additionally, a contingency reserve must be considered. Then the dimensioning of the battery and generator can be calculated and the design goals for the involved components validated. As this project is a work in progress, this phase is not yet completed.

6. Conclusion

Today, the validation processes for complex products are becoming more and more complex. The reasons for this are manifold: there is increased product variety caused by the increasing complexity of the customers' requirements, and the increased technical capabilities of the original equipment manufacturer (OEM); furthermore, the integration of multiple domains within one product, like mechanics, software, electronics and service [Lindemann 2006] leads to complex validation processes. Due to increasing technical capabilities and manifold customer requirements, OEMs are expanding their product variety in order to increase profits [Firchau 2002]. Simultaneously, increasing time and cost pressures are forcing OEMs to streamline their validation processes. Due to the large product variety of some products, one approach is to perform product tests with a small subset of the product variety [Schwankl 2002]. Accordingly, the validation methods must use the analytical results in order to derive properties for the remaining variants. This requires knowledge about the application's impact on the components' properties on the one hand, as well as knowledge about its impact on the composed product property on the other. The required information can be gained by analyzing and interpreting product tests. There are various methods available to support several subproblems that must be considered when evaluating product properties, but there is no systematic approach that contains methods for the subproblems described above. This paper presented a five-step procedural model for evaluating product properties according to the product's application and the components' characteristics. All of the phases contain methods to provide information that must be considered during the validation process for complex products. The focus of this paper is the analysis of product applications and their impacts on components' properties. To this end, the authors present a combination of influence models, variance analysis, correlation analysis and clustering. The presented case study is a work in progress. In future work, the authors will focus on refining the presented phases. In particular, the quantification of influencing factors using DoE and the synthesis phase will be developed. Moreover, the authors will apply the presented procedural model to further products.

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References

Andreasen, M. M., Synthesis Methods as System Basis – a Contribution to a Design Theory (in Danish). Dissertation, Lund University, 1980.

Boardman, J., Sauser, B., "System of Systems - the meaning of of." System of Systems Engineering, 2006 IEEE/SMC.

Firchau, N. L., Franke, H.-J., Huch, B., Menge, M., „Variantenmanagement: Variantenvielfalt in Produkten und Prozessen erfolgreich beherrschen", Hanser-Verlag München, 2002

Ford, A., Flynn, H., "Statistical screening of system dynamics models." System Dynamics Review 21, 2005.

George, E., Box, P., Hunter, J. S., Hunter, W. G., Statistics for Experimenters. Design, Innovation, and Discovery. 2. Auflage. Wiley & Sons, Hoboken NJ 2005,

Kececioglu, D., "Reliability Engineering Handbook" Prentice Hall, Inc., Englewood Cliffs, New Jersey, Vol. 1, 1991.

Klein, B., "Versuchsplanung - DoE. Einführung in die Taguchi/Shainin-Methodik" 2. korrigierte und erweiterte Auflage. Oldenbourg, München 2007.

Lindemann, U., „Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden" Springer, Berlin, 2006.

Lindemann, U., Maurer, M., Braun, T., „Structural Complexity Management" Springer, Berlin, 2009.

Rezayat, M., "Knowledge-based product development using XML and KCs", Computer-Aided Design 2000.

Schwankl, L., "Analyse und Dokumentation in den frühen Phasen der Produktentwicklung" Dr.-Hut, München, 2002).

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