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Reduction of Uncertainty by Sensitivity Analysis and context-specific Data Processing within Virtual Property Validation

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Abstract
Particularly, in the early stages of a development project, designers have to deal with a comparatively high data uncertainty. Virtual product development is essentially dependent on simulation results, which in turn are strongly influenced by the underlying database. In this paper the utilization of sensitivity analysis in combination with a specific data processing is shown. This gives methodical support to reduce uncertainty at hand.

Keywords: uncertainty, data quality, sensitivity analysis, data processing

1 Introduction
Simulation methodology is an appropriate device to gain knowledge about real systems through models. Experiences from several industrial projects show, that the multitude of methods and tools are well-known and widely used indeed, but, an efficient coordination between development teams concerning available data for simulations is missing. In terms of cost and time savings, an early and simultaneous validation of product functionality is to seek. But, especially in the early stages of the product development data and information are uncertain and incomplete; in this context it will be absolutely necessary to indicate which input data the simulation results are based on in order to prevent systematic errors and avoid implying a precision that does not exist [1]. This results in the need for a simulation planning as a parallel process with the objective to optimise the integration of methods and tools of simulation into the development process. Therefore, the aim of current research activities is to develop a holistic approach for the continuous validation of product properties throughout the development process by means of simulations.
In this paper the utilization of sensitivity analysis in combination with a specific data processing is shown. The latter is based on [2]: the developer determines characteristics (“set-screws” to directly influence a product) as a task within the synthesis; these must be verified by analysing the resulting properties. As product data only occur in the progress of the development, this approach will be extended to get a stronger context-specific/operational link to the development status and processes. Sensitivity analyses will be used to provide a better understanding of how the product properties depend on characteristics. Consequently, the meaningfulness of a simulation at hand can be evaluated and appropriate “set- screws” can be identified to execute iteration loops more goal-oriented.

2 Sensitivity analysis
Sensitivity analyses examine the correlation between input and output parameters in a system [3] [4]. The effect of the input parameters on the system response is evaluated by varying the

input parameters [5]. Nowadays, sensitivity analyses are used to analyse uncertainties of input parameters (interpreted as disturbance variables) and to include estimations of the model [6]. In general, the following objectives are focused on by means of sensitivity analysis [3] [6]:

- *model validation:* validity statement relating to reality
- *identification of important input parameters:* qualitative/quantitative ranking of input variables relating to their influence on the output parameters
- *elimination of unimportant input parameters:* reduction in complexity by identifying negligible parameters [5]
- *identification of model properties:* e.g. monotonicity; dependencies between the input variables that are caused by the model
- *identification of the critical design space:* display areas within the design space where the system response is not permitted [5]
- *model optimization:* identification of important and less important input variables; improvement and complexity reduction
- *risk assessment:* limit function at which the model fails to identify responsible input variables

2.1 Utilization of sensitivity analysis in the context of simulation planning

In the following, the most important methods of sensitivity analysis are briefly described to explain their operation and show their results. This is the basis to assess respectively classify them with respect to the support of simulation planning. For more detailed information in this area see e.g. [3] and [7].

The ***factor screening*** determines the qualitative influence of input parameters and model on the output parameters. That way, parameters with a high influence on one or several output parameters can be separated from those parameters that have less influence: they are often applied in the context of global sensitivity analysis to reduce the computational effort by deleting less important parameters from the equations. For example, the one-at-a-time (OAT) design measures system response related to the variation of one input parameter. Additionally two extrema that can be interpreted as the limitation of the factor space can be identified. If parameters are combined into groups, the effective correlations between the parameters retain.

By means of ***local methods*** a local sensitivity index is calculated with respect to one specific output (e.g. critical minimum or maximum, optimum). Derivations of differential equations respectively differential coefficients and difference quotients are the resulting sensitivity indices. For the evaluation of one input parameter a column vector occurs, a row vector when evaluating one output parameter. By means of the normalized standard deviations of the input and output parameters, the weighting of the input parameters is realized. This means that a column vector shows the relation between a characteristic and a multitude of properties and a row vector shows the relationship between several characteristics and one property. ***Global methods*** are valid for the entire model range, which in turn leads to model independence. Furthermore, it is possible to vary more than one input parameter and analyse their influence on the output parameters [4]. The *regression analysis* is used in general when an output parameter "y" is of interest and one or several input parameters are varied. The strength of the correlation can be quantified. This allows to identify input parameters, that have no influence, respectively, several input parameters that include redundant information with respect to "y". An error term considers disturbances based on the model , as not every behaviour of the output can be described only by the influence of input parameters (e.g.: in reality, there are additional disturbances, such as an energy loss through friction). The standardized regression coefficients describe the sensitivity. *Variance-based methods* can be used regardless of any restrictions and calculate a quantitative sensitivity measure. Several input and output parameters can be simultaneously analysed. A differentiation between main effects (so-called 1st order sensitivity indices, the influence of a parameter to the variance of the output parameter) and total effects (so-called aggregate effects that characterize correlations of the input parameters) is possible and variance-based methods additionally work regardless of the model properties. It is possible to gain knowledge about important and unimportant parameters to optimize the model. When assessing the risk it is focused on keeping the output value within a target variance in the focus of attention. *Graphical methods* exist as well: scatter plots are mainly used to identify and characterize dependencies between two parameter features. They can also be grouped into matrices so that a comparative view on the form of dependencies is possible. Furthermore, several scatter plots can be overlaid and combined. Consequently, sensitivity statements regarding to certain configurations of the input parameters are possible.

In the ***context of the simulation planning***, this means that the input parameters of a sensitivity analysis basically represent the ”set-screws” of the developer and their influence on properties (output variables of a sensitivity analysis) is shown. Consequently, the results of a sensitivity analysis are variances of the properties as a function of variances of the input parameters (these are not characteristics in every case; see chapter 3.2). The interaction of “set- screws” and obtained product properties is getting more transparent. Table 1 shows how the different methods of sensitivity analysis will be used in the context of simulation planning; the example in the following chapter illustrates the utilization and benefit.

Table 1: Application of sensitivity analyses based on [10]

Method	**Focus of Use**	**Benefits**
Factor Screening	• determine the qualitative (high/less) influence of input parameters and model • reduce the computational effort in the context of global sensitivity analysis	• get a basic prioritization of the parameters → useful when the developer has no information which characteristics are the decisive „set-screws“ to achieve required properties • only the most essential parameters are evaluated in terms of quality and integrated into the decision-making process
Local Sensitivity Analysis	• sensitivity of several input parameters concerning a specific value of the output • provide an indication of combinations of characteristics that lead to critical/unwanted product properties	• low computational effort → applying local methods when analysing complex models • indentify correlations between the input parameters • receive indications of the values margin of characteristics to optimize the solution
Global Sensitivity Analysis	• analyse the entire design space of available parameters • vary more than one input parameter	• get a basic prioritization of the parameters • identify and quantify correlations • include model disturbances

2.2 Example of use

The exemplary use of sensitivity analyses is shown by the behavioural simulation of the break application of a car with an anti-lock brake system (ABS) [10]. The aim is to analyse the impact of changes in selected parameters (mass **„m“**, tyre radius **„r“** and front area of the car **„A“**) on the security relevant breaking distance in a qualitative way. The results are shown in Figure 1 (x-coordinate: time; y-coordinate: breaking distances; corresponding table of values): for reasons of clarity, the explicit representation is restricted to limit values and mean value of the chosen value ranges.

Figure 1: Results of the sensitivity analysis

This example shows that sensitivity analyses can raise transparency in the context of decision-making processes and also give specific advice with respect to an appropriate link-up to the process model or milestones, as follows:

- **„m“** has a significant influence on the breaking distance (difference of 1,75m in the analysed range), **„A“** and **„r“** have a very small influence
  → simulation of the breaking distance has to be executed whenever significant changes in **„m“** occur
  → practical to link-up considerations concerning property validation with specific repetitive meetings that focus on **„m“** (standard of car development)
- Changes must be viewed in the overall context of the car, thus intensive communication between distributed development teams is required;
  → the effect of parameter changes in the context of necessary design changes is shown or even ranges for parameter changes can be possibly determined.
- Design changes of **„A“** are less relevant in the context of the brake performance; a surface change of 0,8m^2 only causes a change in the braking distance of 0.16m.
  → the usefulness of the simulation is only given in severe design changes (rather rare): it is not stringently necessary to use actual design data when a property validation is triggered by mass changes.
- **„r“** was analysed in the range of standard wheel and tyre combinations and can be considered to be even more uncritical
  → here, a different focus should be set (e.g. dynamic stability)

It should be noted that only a single property was focused on in this example. This is common practice in the context of property validation; however, the overall context of product properties has to be considered: e.g., **„r“** (and a related design change) has certainly more influence on the driving comfort, but, that is object of another analysis.

2.3 Reduction of uncertainty by process integration of sensitivity analysis

The detailed FORFLOW process model (described in detail in [8]) that got constant positive feedback from industry partners provides the basis for a holistic approach for simulation planning: it is globally oriented to meet current challenges (e.g. situation-specific process planning), but nevertheless it is detailed and variable. The process flows are not fixed entirely, but can be adapted to some degree. A simulation planning requires such a detailed and flexible process model to efficiently integrate simulation methods into the development process. This also applies to the integration of sensitivity analyses as a support for simulation planning. The models used for property validation can also be used for sensitivity analysis. In the context of simulation planning, sensitivity analyses offer the following benefits:

- The confidence in the model and its predictions is increased by providing a better understanding of how the model output depends on changing input [3].
- The developer can focus on the relevant “set- screws” to improve his solution (iteration management). The development risk that requirements are not fulfilled decreases.
- Increasing sensitizing and proactive data management within the product development: data providers/consumers become more aware of the relevance of data to be provided, respectively, the utilization of a certain data quality [1].

If simulations are to be employed reasonably, a pre-defined data quality with respect to both completeness and certainty is needed [9]. Simulation results have always to be evaluated with respect to the currently available (input) data and information quality, and, therefore, are always subject to uncertainty. This can be considered to be quite critical when the task management (e.g. iteration management) of virtual development processes is mainly based on simulation results. The combination of the specific data processing based on [2] and the results of sensitivity analyses will be used (e.g. for a weighting) to evaluate the prevailing data quality: the approach to the underlying evaluation of simulation results can be found in [1] and [10]. It is aimed to more transparently describe simulation output, based on the importance (sensitivity measures) of design parameters in conjunction with their quality assessment, to make them assessable and reduce respective uncertainties. In addition, it is indicated by the sensitivity analysis at what values of certain input parameters the ranking of alternatives is changing under the influence of multiple (partial conflicting) goals and an uncertain future and, therefore, other alternatives should be preferred. This in turn will support simulation planning as well as the determination of targeted iteration loops to improve the designer's solution. Consequently, development time and risk are reduced. In this context the integration of dynamic product models, that are connected to the process step, is required which is supported by the FORFLOW process model. This is important as on the one hand data have different levels of concretization within specific development phases and on the other hand different objectives are focused on in terms of property validation.

3 Classification of development data and link-up to sensitivity analysis

Essentially, there are two kinds of process steps in product development that are executed alternately: synthesis and analysis. This distinction is closely connected to different data types which have to be clearly differentiated in the data model and are interesting due to their tight linking to process considerations as well [11].

3.1 CPM/PDD approach according to WEBER

The CPM/PDD-approach of [2] differentiates between two categories of data with respect to the process step: characteristics and properties. Characteristics occur as a result of the synthesis process and serve as input values for the analysis process in its result properties emerge. Thus, characteristics represent those "set-screws", with which the developer can determine and directly influence a product [2]; properties can be influenced by the developer only indirectly via a modification of characteristics. Characteristics define a product by its structure, shape and material consistency: for example, if geometry and material of a component are defined as characteristics, appropriate component properties such as weight or strength are a logical consequence of previous decisions [2] [12].

This approach offers the following advantages [10]: the CPM-approach establishes the relation between required/actual product properties and characteristics as the designer's "set screws". The PDD-approach deals with the underlying development processes; considerations of interdependencies between product and process support the efficient implementation of development activities and complete the overall context.

3.2 More detailed classification of development data

Initial studies show a network-like linkage of characteristics and properties and among each other, which can be prepared by matrices. However, a more sophisticated categorization of development data seems to be necessary in order to support the data processing [10]: we need to clarify in which case data have to be treated as characteristics or properties; here, a dependency on both hierarchy level in the product structure as well as focus of property validation is shown. With regard to the example in section 2.2 it can be noticed that the mass of the car **"m"** is used in the sense of a characteristic as an input parameter ("set-screw" for the break distance) in the simulation context and is a decisive parameter to influence the brake performance. However, **"m"** can only be influenced by characteristics at a lower level of the product structure. In addition, such data processing is expected to disclose advanced and more detailed ways to design a sustainable evaluation system and to link sensitivity analyses to the FORFLOW process model.

Table 2 shows the initial approach of a more detailed categorization of characteristics and properties with the example of a mechanical seal: direct characteristics can be influenced in terms of [2], indirect characteristics can only be used to modify properties in a broader sense as they depend on decisions (e.g. product strategy) made before. According to [13] secondary properties are influenced/caused by other (primary) properties, primary properties are independent variable. Therefore, direct properties can be considered as primary properties in a broader sense of [13]; indirect properties as secondary properties. However, the basic definition of "property" according to [13] is based on a different way of thinking compared to [2] or [12]. This approach of a more detailed classification of development data shows promise to get a closer link to process and product structure. This is to verify with various examples at present. In this context, a difference of dependencies is noticed: the dependencies between characteristics and properties result from other sources than e.g. the dependencies between characteristics (screw/hole diamater): whether a more detailed classification is necessary or helpful is expected as a further result of the validation phase.

Table 2: More detailed classification of development data

Data		Characterisation	Example „Meachnical Seal"
Characteristics	direct	• original character, can be directly determined by the developer	• external diamater of the seal ring
	indirect	• are influenced by other characteristics; cannot be directly influenced • characteristics are determined by product strategy (e.g. use of standard parts, common parts , repeat parts)	• the choice of screws at positive torque application determines the hole diamater • dimensions of the stationary seat by use within different mechanical seals
Properties	direct	• result from direct characteristics; can be directly influenced	• the choice of material influences dry running characteristic
	indirect	• result from indirect characteristics; cannot be directly influenced • result from direct properties	• frictional heat within seal gap bei take-over of a stationary seat • friction resistance depends on dry running stability

3.3 Context-specific data processing

The main requirements to an appropriate data model (Figure 2) in the context of simulation planning to include specific aspects as well as the overall context are:

- display the dependencies between characteristics and properties and dependencies among each other
- include the results of a sensitivity analysis (impact of characteristics on properties)
- display actual properties and reference properties
- include the overall quality of current development data as well as the quality of individual criteria (uncertainty analysis of characteristic and reference properties)
- appropriate link-up to meta data: responsible persons, history of modifications, source of reference properties (e.g. specific DfX-guideline) and characteristics (e.g. previous product versions), utilization as input/output data for process steps/property validation,...
- enable an additional column- and row-level grouping to provide a clearer display: e.g. referring to components/assemblies, DfX-guidelines/criteria, domain-specific views within mechatronic context, specific property validation, process step/responsibilities,...

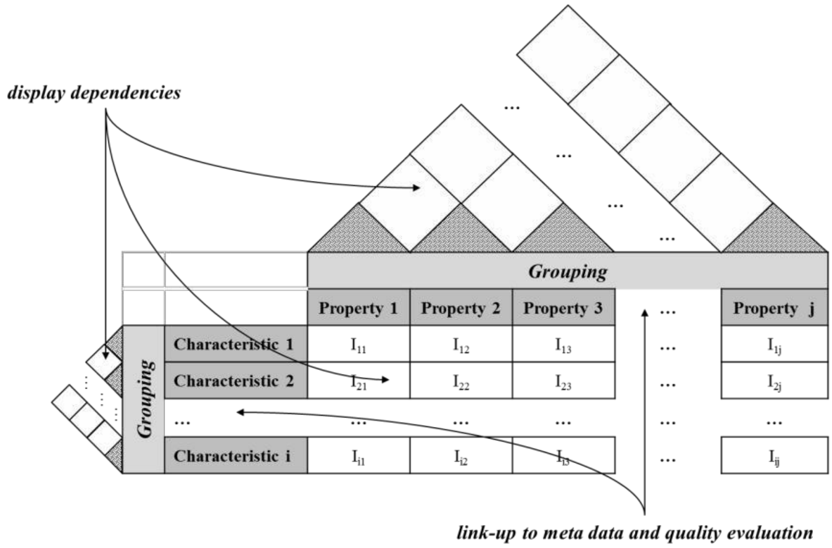

Figure 2: Context-specific data processing by matrices

The practical integration of the data model in a product data management system is certainly intended. This ensures not only the data consistency, but, can be e.g. also used to export excel files with the link-ups of a specific characteristic to other characteristics or properties: this gives the developer a quick overview to be aware of the impacts of changes.

4 Summary

Sensitivity analyses enable to reduce uncertainty and support simulation planning as it is pointed out to which extent individual parameters are important to achieve required product properties. The process linkage is realized through the available data and information related to the process step. Consequently, property validation can be controlled in a more targeted way, as more detailed statements about appropriate „set-screws“ to optimize a designer‘s solution are possible.

As shown before the meaningful application of sensitivity analysis, however, is bound to an appropriate and verified way of data processing. This is the main objective of current activities that focus on different product examples. This serves not only as a verification of previous considerations, but, certainly will give new insights concerning further research and modifications. For example, an open question is whether dependencies must be specified respectively displayed more precisely as well: if the developer decides to use a specific screw the hole diameter has to be accordingly determined (a kind of bidirectional dependency, a parallel determination and modification of characteristics, can be assumed); characteristics that are determined by product strategy or the resulting density based on the determined material can be regarded as unidirectional dependencies. Here it must be clarified whether a concretization is useful or related to the more detailed classification of development data and, therefore, already integrated.

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