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UNCERTAINTY CONSIDERATIONS BY CONTEXT FACTORS FOR THE MONITORING OF THE DEGREE OF PRODUCT MATURITY

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Keywords: uncertainty, design structure matrix, property validation, maturity management, early design, decision making

1. Introduction

The increasing complexity due to technological progress, the increasing customer expectations, the increasing need for shortening the development time as well as cost pressure caused by global competition are leading to difficult challenges in product development. Hence, product developers have to cope with these challenges as efficiently as possible.

1.1 Problem description

These challenges occur particularly in the design engineering process because this is, according to [Hubka 1976], a knowledge and information handling process and, according to [Ehrlenspiel and Meerkamm 2013], a process of information acquisition, processing and sharing. According to [Clark and Fujimoto 1991], the product development process (PDP) is analysed as a data processing process. The focus of this paper is the product planning phase according to [Clark and Fujimoto 1991]. The information required is highly uncertain because its content is often largely based on assumptions, particularly at the beginning of the PDP. The level of uncertainty is compounded by the possibility that certain facts and figures may be completely unknown or disregarded [De Weck et al. 2007]. Hence, the identification of sources of uncertainties, the determination of the uncertainty types and the evaluation of their effects are representing important challenges. Moreover, the unavoidable use of uncertain information during the PDP complicates the detection of the real product's degree of maturity. While the corresponding parameters in terms of economic and temporal targets can be measured during the project relatively easily, the determination and monitoring of the technical development status is fraught with difficulties due to the lack of parameters and insufficient consideration of uncertainties.
A continuous validation of product functionality during the development process must be ensured. This can be achieved by virtual property validations. Knowledge about real systems can be gained by using simulation methods. However, data quality must be pre-defined with respect to certainty and completeness depending on the current process step if simulations are to be executed efficiently [Reitmeier and Paetzold 2011]. Consequently, no wrong accuracy of the simulation results is suggested and the succeeding estimation of the realized product maturity is supported. Depending on the process step, situation-specific approaches are required to handle development processes efficiently.

1.2 Objectives

As a result of these challenges, it is the purpose of this paper is to present a novel approach by using a matrix-based product description (MBPD) for the integration of uncertainty and contextual factors (CF) in the detection and monitoring of the degree of product maturity. The first objective of this work is to develop a concept for the identification, the quantification and the handling of uncertainties in the development of a product by taking different sources and types of uncertainties into account as well as to integrate these results in the measurement of the degree of maturity of a product. A comparison of the properties required and the properties realized during the development process provides information about the current degree of product maturity for the technical project leader, who is the main user of the uncertainty measurement and the monitoring of the product's degree of maturity. The focus of this approach is the product regarding its (technical) properties, and therefore other performance criteria (e.g. regarding development time and costs) are not considered.

The second aim is the consideration of CF which will be integrated into the MBPD in order to facilitate the situation-specific planning of process steps (e.g. virtual property validations). By using the MBPD, it is not only possible to analyse which properties are resulting from which characteristic specifications but also to identify what dependencies and interactions between characteristics, properties and behaviour of a product exist. Thereby, characteristics are used by developers to define the product and so they determine, among others, the geometry (e.g. shape, dimensions) and material (e.g. steel, plastics). Properties resulting from the definition of characteristics have a determining influence on the behaviour of the product during its later use. The MBPD is both the starting point for an approach for simulation planning as necessary data for a specific validation can be identified [Reitmeier and Paetzold 2013] and the basis of the subsequent evaluation of the product's degree of maturity.

2. State of the art and related work

2.1 Matrix-based product description

As outlined in detail in [Krehmer 2012], none of the existing procedural models known from the literature enable the detection and monitoring of the product's degree of maturity concerning the entire product and throughout the whole PDP. Merely the Property-Driven Product Development approach according to [Weber 2005] and the Function-Behaviour-Structure Framework according to [Gero and Kannengiesser 2006] consider certain aspects that were used as a basis for the monitoring of the product maturity [Luft et al. 2013]. Therefore, the overall objective of the authors was to develop a procedure model in particular for iteration and product maturity management in the property-based product development, which guides product developers step by step through the property-based PDP. The MBPD is the most important part of this procedure model which was proposed by [Krehmer 2012] and was further developed and validated in [Luft et al. 2013] and [Luft and Wartzack 2013]. Developers are guided step by step through the entire property-based PDP by the procedure model which consists of 33 single process steps. These steps are mainly focused on the required property profile of the product which leads to a consistent orientation towards the relevant customer requirements (for further details see [Luft et al. 2013]). A specific micro-cycle is performed within each of these 33 steps. These micro-cycles provide assistance in the execution of each step and support the developers to fill out the MBPD with the required information (for further details see [Luft and Wartzack 2013]).

Consequently, the MBPD (Figure 1) is – starting from the customer requirements (REQ) – step by step filled out with information regarding the respective behaviour (B), properties (P), characteristics (C) as well as the function structure (FC) and active structure (AS) of the overall system level (OS), the subsystem level (SS) and the component level (CP). The main advantage of the MBPD is the mapping of multiple dependencies, for example, of defined characteristics and resulting properties. Hence, deviations from required properties together with their related causes can be recognized early. So, better alternatives can be identified and their corresponding effects can be estimated accurately. With respect to virtual property validations, the MBPD helps to identify necessary input data for specific simulations. In addition, the effect of modifications of characteristics on properties (not only the original intended ones) is cognizable and that is important to identify which properties have to be validated again. The fulfilment of the required property profile can be monitored because of the consequent detection and calculation of the product maturity by using the MBPD at each process step. Therefore, the need for action can be detected at an early stage, for example, to avoid avoidable iterations during the PDP (for further details see [Krehmer 2012]). But, the MBPD and the MBPD for iteration and particular for product maturity management include no uncertainty considerations so far.

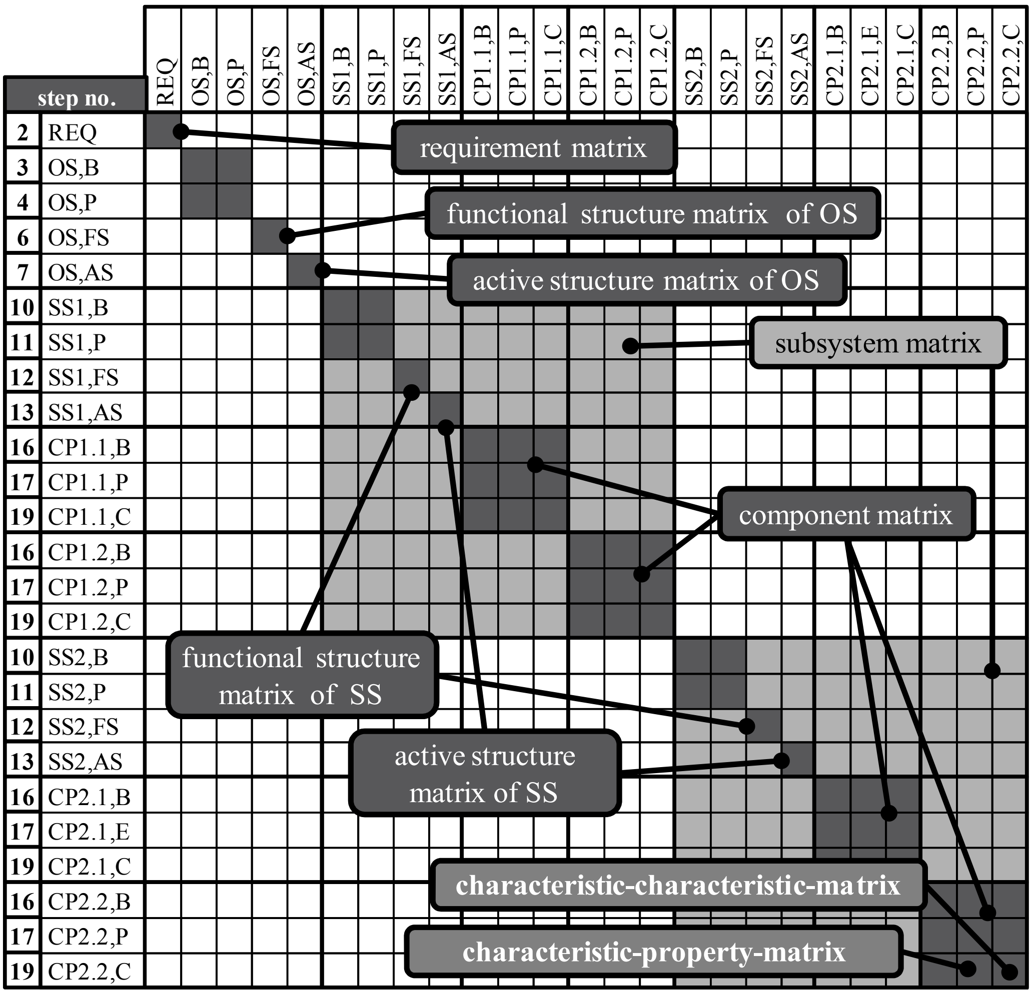

Figure 1. Simplified and schematic overview of the MBPD according to [Krehmer 2012] and [Luft and Wartzack 2013]

2.2 Analysis of the development situation by context factors

A key challenge is to develop an approach to validate product properties efficiently. A multitude of highly efficient simulation tools is available, but it is still an open question which simulations can be executed at what point in time to really support PDPs by purposeful and early validation of product functionality [Paetzold and Reitmeier 2010]. In particular, the usefulness of simulation is highly dependent on the quality of available data and information which in turn depends on the particular process step.

Therefore, a situation-specific approach is required to evaluate the available data basis to support the decision-making process concerning the execution of an intended simulation. According to [Roelofsen 2011] and [Ponn 2007], there is no universal description of the development situation, however, a tendency to describe situations by means of defined factors, which are adapted to the respective situation context. Consequently, CF (tab. 1) were determined to describe the present situation with a specific view to the execution of simulations (for further details see [Reitmeier and Paetzold 2013]).

Table 1. Different CF [Reitmeier and Paetzold 2013]

with reference to the **product**: evaluation of the current development status	(1) design space characteristic (2) relevance characteristic (3) design space property (4) relevance property	(5) origin of the reference value (6) relevance of validation (7) product complexity (8) novelty
with reference to the **process**: support of the simulation planning and the evaluation of simulation results	(9) revision state of data (10) availability of data (11) input quality of data (12) processing state of data (13) design data: authorized person	(14) simulation: authorized person (15) simulation: output quality (16) simulation: model quality (17) simulation: focus (18) simulation: level of abstraction
with reference to **resources**: identification/allocation of available resources	(19) simulation tools (20) competence of the personnel (21) simulation effort	(22) available capacity of tools (23) available capacity of personnel

These CF address all important aspects to support decision-making situations with regard to the execution of virtual property validations. Accordingly, an efficient approach to simulation planning was introduced in [Reitmeier and Paetzold 2013]. However, the CF still need to be linked to the MBPD (see chapter 4.2).

2.3 Connection of simulation results and product maturity management

In the (mainly) virtual PDP, simulation results are essential to determine the degree of the product maturity. But, these results are highly depending on the quality of available or used data and information. As a result, decisions are influenced by the quality and uncertainty of the information used. For this reason, an appropriate multi-criteria evaluation system was introduced in [Reitmeier and Paetzold 2011] to identify the realizable output quality of simulations in the following way (Figure 2): input data which are required to execute a specific property validation will be identified via the MBPD (see chapter 2.1). If data are not available, the quality level "0" will be assigned. If data are available, a quality evaluation concerning different attributes of quality (e.g. accuracy, completeness) is operated and a quality level in the range of]0; 1] (i.e. [0%; 100%]) is assigned. These quality attributes are based on an empirical study of [Wang et al. 1996], an often cited and used concept for describing and evaluating data and information quality. Based on the weighted relation of the required input and output data (apparent from the MBPD or a sensitivity analysis of the already existing and used simulation model), a correspondent realizable quality level of simulation results will be calculated.

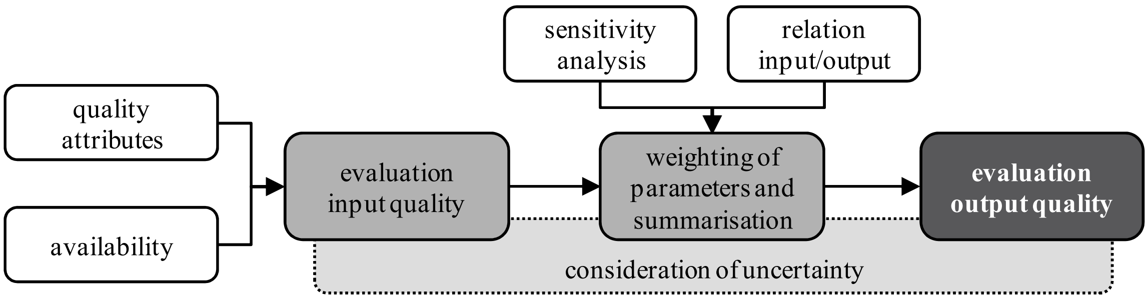

Figure 2. Evaluation system of data quality, based on [Reitmeier and Paetzold 2011]

This evaluation system was not established with the focus to identify and to describe quantitatively "uncertainty". Nevertheless, it considers aspects of uncertainty by including the mentioned quality attributes (e.g. accuracy) and the weighted relation of input and output (which is not always obvious and transparent). This will be addressed in chapter 4.1 in more detail.

3. Integration of uncertainty considerations

3.1 Definition and importance of uncertainty

However, before starting with this topic, some general remarks and definitions are required to provide a basic understanding of the term "uncertainty". Uncertainty is not only a permanent companion in daily life but also a problem that arises during information acquisition and processing in the PDP. Almost every statement and all information are subject to a more or less high degree of uncertainty. Therefore, any uncertainty that comes up during the PDP is attributable to information that has an uncertain nature in some way, whether as a result of incompleteness, ambiguity, unreliability or other reasons. This is due to the fact that most of the information that will be used during the PDP has a high degree of uncertainty (particularly in radical innovation processes). [Earl et al. 2005] clarify this with the following words: "Uncertainty is present within all areas of design and designing (products, processes, users, organizations). [...] A key problem in design is the estimation of [...] uncertainties in unique products and processes".

Since data or information is often not or only insufficiently available during the development of new ideas and concepts for products, developers must ordinarily make estimations or assumptions [Eifler et al. 2012]. If this range of uncertainties is not considered sufficiently during the product development, this may have far-reaching consequences for the development project; especially as decisions in the early stages of the development have a major impact on cost, quality and time. If it turns out at the end of the PDP that certain assumptions are wrong, the product is faulty or important information were simply forgotten, time-consuming iterations in earlier phases will be required which leads to scheduling shifts and usually high rejection and reworking costs [Keller et al. 2007]. Since the occurrence of these problems is closely related to the project-specific uncertainty, the reduction, and, if possible, the avoidance of these uncertainties has a very high priority in product development. This shows the necessity to develop an approach that helps to identify uncertainties completely and supports to handle these efficiently in the context of product development. However, as uncertainties differ in source and type, it is necessary to develop a systematic approach that divides uncertainties into certain categories and to identify their effects in the following.

3.2 Classification of uncertainties in the product development

The first question that arises in the consideration of uncertainties is: What causes uncertainties in product development and which sources can be determined for this? There are numerous approaches in literature for answering this question (e.g. [MacCormack and Verganti 2003], [De Weck et al. 2007], [Kota and Chakrabarti 2007]). The variety of approaches shows that the determination of sources, the assignment of the uncertainties and their evaluation are always based on a specific focus (cf. also [Eifler et al. 2012]). This also applies to the following explanations.

In this approach, the initial distinction is made between internal and external uncertainties. Between these two sources exists a large difference in terms of influenceability of uncertainties (internal and external are related to the company's perspective). The distinction is to be understood only as a rough guideline, as certain sources (e.g. product life cycle) cannot be matched strictly to one or the other source of uncertainty. This differentiation is particularly important for the derivation of strategies for handling uncertainty because the possibilities of reducing uncertainty are decreasing more and more with the increasing external character of uncertainty sources. In addition to this basic distinction, five main sources are defined. Each includes several subcategories of uncertainty sources (Figure 3). As the focus of this work is on the PDP, in particular the product inherent uncertainties and partly the uncertainties from the business organization are of interest.

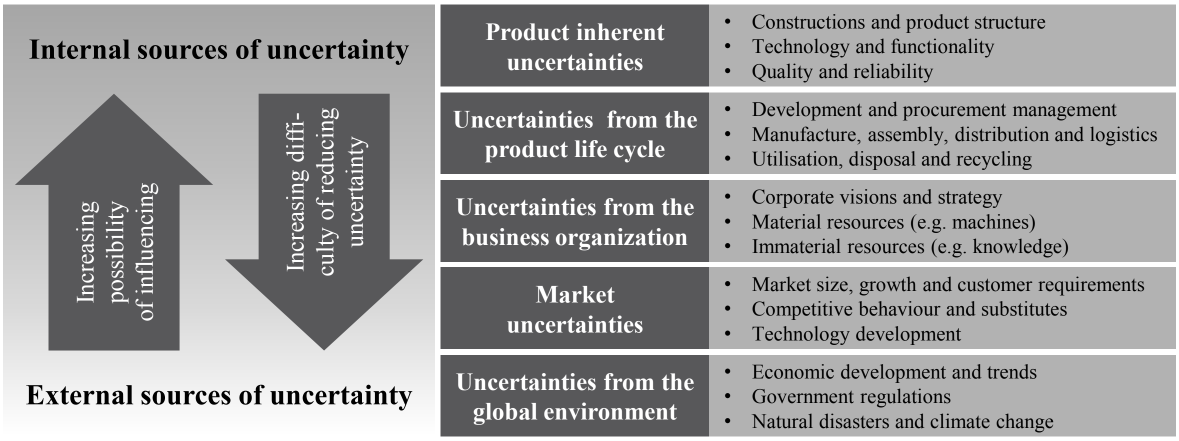

Figure 3. Main sources of uncertainty

When considering uncertainties during the PDP, not only the various sources of uncertainty have to be included but also the different uncertainty types for which many approaches can be found in literature (e.g. [Earl et al. 2005], [Zimmermann 2000]). Concerning an integration of uncertainty aspects (in a broader sense) in the context of simulations, the quality attributes of [Wang et al. 1996] were picked up in chapter 2.3. These refer to the information content uncertainties and can be also found in a similar manner in [Derichs 1997]. The content of uncertainty can be subdivided in three categories: missing information (e.g. incompleteness), incorrect information (e.g. unreliability) and misinterpretation of information (e.g. ambiguousness). But, [Derichs 1997] additionally picks up uncertainties with reference to the context since in his opinion "uncertainties can occur at two different levels of human information processing" (Figure 4). While the former aspects only refer to the actual content of the information (e.g. the shaft diameter is between 40 and 60mm), context uncertainties arise from the subjective assessment of the reliability and meaningfulness of the information content (e.g. is the information "shaft diameter is 40mm" correct?). In this case, the recipient who interprets the information content un-/consciously uses his knowledge of the context in which it stands.

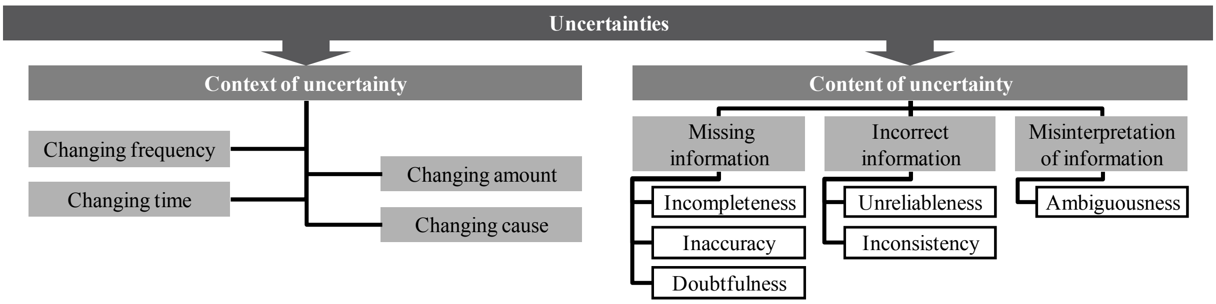

Figure 4. Uncertainty types based on [Derichs 1997]

According to [Ponn 2007], "the development context is the surrounding context of the PDP that can be described by CF that have an influence on product and process". Therefore, CF were determined to describe and analyse the particular situation in the context of simulations. The contextual considerations of [Derichs 1997] will be used to amend this specific collection of and to develop an extended analysis. For this purpose, the CF listed in Table 1 are complemented by the CF "changing frequency (24)", "changing time (25)", "changing amount (26)" and "changing cause (27)".

3.3 Methodological approach for the evaluation of context uncertainties

Context uncertainties introduced above, which arise during the processing of information, are requiring appropriate methods that can be used to capture and represent the uncertainties. These methods must allow a quantifiability and comparability of the different uncertainty types. This poses the following three questions: How to assess different uncertainty types? How to determine individual uncertainty contributions? How to collect and assess the degree of uncertain information so that further mathematical operations and comparisons with other uncertainties can be conducted?

Each uncertainty type (e.g. "changing frequency") has to be described with reference to specific criteria, for example, an average value for expected changes for a component (e.g. "in former projects the shaft diameter changed 14 times"). However, the aim is to derive a single, comparable and optionally summable measure which describes the extent of uncertainty of information. For this purpose, a relationship between the so-called uncertainty degree (UD) and the respective criterion of the uncertainty type is required. The UD is a measure between 0 and 5 and describes the extent of uncertainty of information and can assume values in the interval [0; 5] (for better illustration only integer values in this paper; other intervals may be used as well). It should be noted that the individual UD have to be normalized. The value of UD stands in a positive relation to the uncertainty extent. The UD can be used both to describe the uncertainty of specific information (e.g. UD_I) as well as to represent the complete uncertainty of a development project.

The correlation between the UD and the criterion for mapping the uncertainty is achieved via the uncertainty function (UF). The UF is a graphical illustration of the correlation between the UD and the criterion of uncertainty type. It is limited to the range [0; 5] and is used to determine the UD of information in consideration of the selected expression of this criterion. Depending on the value of the criterion of uncertainty type, a specific value results for the UF. This is associated with a corresponding UD which is depending on its respective interval.

The following Figure 5 provides an overview of the correlation between UF and UD and describes the significance of the UD in relation to its value. The shape of the UF, however, can assume a wide variety of variants (e.g. linear, declining, progressive) which have to be set up by means of subjective estimations or experience (if the dependency between the criterion of the uncertainty type and UD cannot be described mathematically). In addition, various probabilistic models (e.g. Monte-Carlo-Analysis) or other (statistical) approaches can be used as well for setting up an UF. This means, for example, that a value for UF ≈ 4.0 belongs to the interval [3.5; 4.5] and is so associated with UD = 4 which implies that the information has a high uncertainty.

Interval of UF	Extend of UD	Meaning of UD
0	0	no uncertainty
]0; 1.5[	1	minimal uncertainty
[1.5; 2.5[	2	low uncertainty
[2.5; 3.5[	3	medial uncertainty
[3.5; 4.5[	4	high uncertainty
[4.5; 5]	5	maximum uncertainty

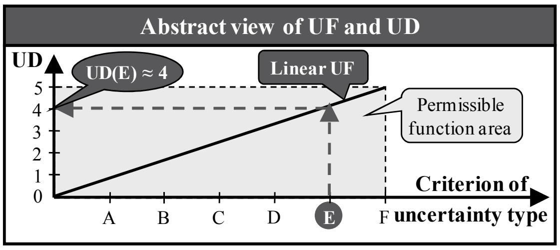

Figure 5. Correlation of UF and UD

Figure 6 presents an exemplary evaluation of context uncertainties. It is important to note that the uncertainty functions, which are used for the determination of the partial degrees of uncertainty, are only examples which have to be adapted to the respective situation (e.g. by using mathematical tools and probabilistic models as known from literature). General rules are not possible because the changing frequencies, times, amounts, and especially causes are highly dependent on the respective information regarding these CF.

By aggregating these individual UDs, the total degree of contextual uncertainties UD_C can be calculated. In addition, this approach offers the possibility to weight the partial degrees of uncertainty depending on individual preferences with different weighting factors (w), see equation 1.

$$UD_c = \frac{w_c \cdot U_1 + w_2 \cdot U_2 + w_3 \cdot U_3 + w_4 \cdot U_4}{\sum_{y=1}^{4} w_y} \quad (1)$$

The advantage of this approach is the ease of classification of uncertainty in a particular class (e.g. low, high) while preserving the possibility to aggregate multiple uncertainties of different sources and types in order to get an overall view of a specific development project. The UD is a modifier for each degree of maturity of which it is subtracted. Thus, the UD_C is an aggregation of all the contextual uncertainties, which affect the different degrees of maturity, and serves for integrating uncertainties in the determination of degree of product maturity. By adding the UD_C with the various uncertainty degrees regarding the content of uncertainty (see Figure 4), the uncertainty (the product properties are in the focus of this paper) of a whole development project can be calculated.

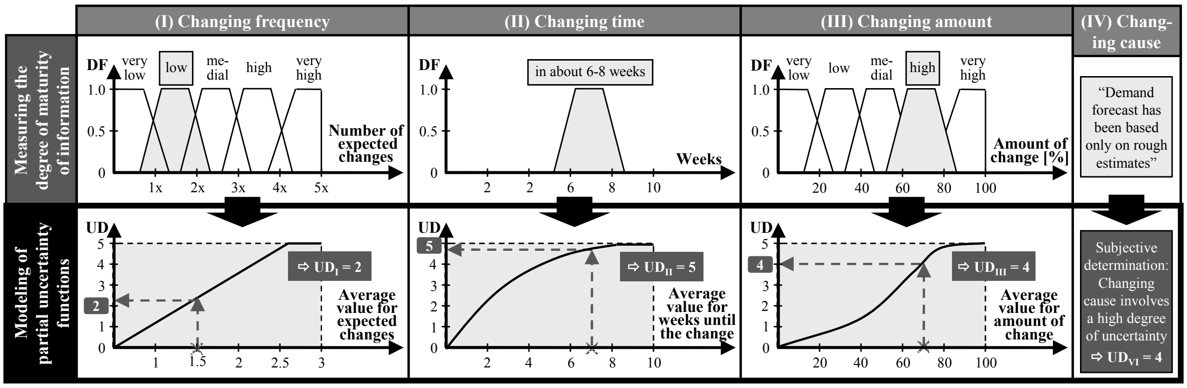

Figure 6. Evaluation of context uncertainties by using uncertainty functions as an enhancement of [Derichs 1997]

4. Utilization of context factors

4.1 Maturity management based on virtual property validations

As mentioned before, the defined CF can be largely used to integrate aspects of uncertainty into the PDP concerning the specific focus on virtual property validations and product maturity management. However, these need to be distinguished or categorized with regard to their objective and utilization:

- **Uncertainty assessment:** corresponding CF 1-5, 7-8, 10-12, 15-20, 24, 26-27
- **Uncertainty reduction:** corresponding CF 5, 9, 13-14, 25

The first category includes CF, which are sources of uncertainty and thus can be used for an identification of the existing UD. The "design space characteristic", which refers to the degree of freedom of a designer to develop a solution, can be exemplarily mentioned. If these is [40 mm; 60 mm] for a shaft diameter, the designer can use a range of 20 mm to create a solution. If the shaft diameter has the status "released" ("processing status" is also a CF), it is available and verified. Consequently, a data quality level of 100 % will be assigned (i.e. the comparable extent of UD is 0). But, if there is no specific value available and a simulation is scheduled, an assumption can be made in the specified range of values. Based on this assumption, a certain UD is present which is evaluated by the data multi-criteria quality assessment mentioned in chapter 2.3. This means, for example, the larger the design space (as one of the criteria: e.g. [30 mm; 70 mm] instead of [40 mm; 60 mm]), the higher the UD concerning a specific assumption (e.g. "a shaft diameter of 45mm will be used for the simulation"). As an example of another criterion, which is integrated in the evaluation system, the person who makes the assumption can be mentioned: the lower the experience, the higher the UD. The more important the shaft diameter for a property to be validated is (e.g. apparent from the MBPD), the higher the uncertainty associated therewith affects the calculated quality of the simulation result (e.g. bending strength). If the estimated overall UD of the shaft diameter is considered to be too high, this may possibly lead to a rejection of a simulation. Consequently, the simulation can be only triggered when a verified shaft diameter is available or a more experienced person made the assumption.

The second category serves to keep such uncertainties as low as possible and to reduce them. The context factor "authorized person (design data)" exemplarily supports if a concrete value of the shaft diameter is missing and the person who is commissioned to execute the simulation will not do an own assumption but tries to get the missing information. The contact details of the person responsible for the constructive design are associated with the characteristic "shaft diameter" (see Figure 7) and consequently an inquiry call or contacting is facilitated. The result can be a released shaft diameter or

a very good assumption due to the higher experience of the employees in the corresponding engineering department.
As mentioned before, the degree of product maturity is highly depending on the simulation results in a virtual PDP. In order to measure this degree of fulfilment, the (uncertain) actual values have to be compared with the specified target values (e.g. of a certain property).
Firstly, consideration of uncertainty in the maturity management is achieved by data quality considerations. The lower the output quality of a simulation is, the more uncertain the degree of maturity. A product has a huge variety of properties that are more or less important for the whole product. Due to the uncertainty analysis in the maturity level of the individual (virtual validated) property an aggregated consideration of uncertainty in the degree of maturity of the overall product is possible.
Secondly, the various UDs represent the identified context uncertainties. The "changing frequency (24)" allows drawing conclusions how often product changes and hence in the degree of product maturity possibly occur. This consideration can be incorporated into the planning of simulations: it gets transparent how often certain properties have to be validated and corresponding (multiple) validations have to be considered. The "changing time (25)" supports a scheduling due to more concrete time ranges can be specified, in which simulations and maturity assessments have to be executed. The "changing amount (26)" indicates how much the degree of maturity can vary from the current value at an upcoming evaluation and can be supported by the MBPD as all correlations within the product are displayed. Finally, the "changing cause (27)" identifies further sources of uncertainty.

4.2 Linkage of context factors to the matrix-based product description

It is obvious that CF provide a significant contribution to an uncertainty analysis regarding property validations and maturity management. However, these must be made available in an adequate manner. For this purpose, the MBPD mentioned in chapter 2.1 is used (Figure 7). From the authors' viewpoint, the two-dimensional extension with another domain would inflate the MBPD too far. Consequently, the CF will be selectively linked to the MBPD in a third layer: virtual property validations use the link-up of input data (e.g. characteristics and/or properties) and output data (e.g. properties) and corresponding CF were defined. Here, basic considerations can be already found in [Reitmeier and Paetzold 2013].

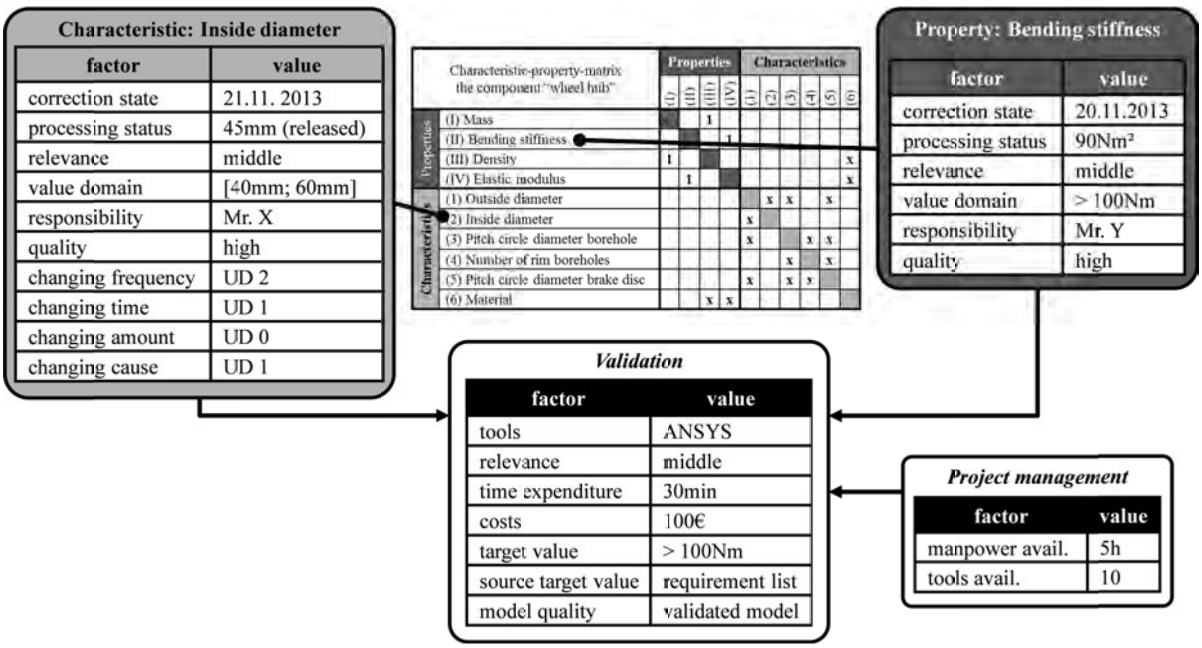

Figure 7. Linkage of CF to the MBPD

The linkage of CF (Figure 7) as metadata to the MBPD supports a quick overview of the present status as all necessary respectively relevant data and information are merged. That way, referring to the previous chapter, the meaningful execution of property validations and the evaluation of the product maturity built on this, is basically facilitated and supported. In addition, a colour coding can be used to highlight precise/critical CF (e.g. with a traffic light scale). For instance, a released processing status is highlighted in green or a low data quality in red.

For the sake of completeness it should be noted that the identification and allocation of available resources should be done with common tools of project management. As this is very different depending on the company, it is not discussed in more detail. The focus remains on the specific data processing of product data and CF which is independent of project management methodologies.

5. Conclusion and outlook

An approach for the integration of uncertainty considerations and contextual factors in the monitoring of the degree of product maturity was introduced. This aims to contribute to the profound comparison of actual and target values during a development project. As a consequence, goal-oriented decision making is supported. Therefore, wrong decisions are reduced and iterations are minimized which helps to reduce development time and costs.

Future research work will deal not only with the application of the approach in a comprehensive industrial case study but also with the further development of concrete uncertainty functions. In addition, computer-based information systems for the MBPD will be validated as well as tools for the (semi-)automated filling of the MBPD will be developed.

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