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UNCERTAINTY-MODE- AND EFFECTS-ANALYSIS – AN APPROACH TO ANALYSE AND ESTIMATE UNCERTAINTY IN THE PRODUCT LIFE CYCLE

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ABSTRACT
Uncertainties in technical systems in the field of mechanical engineering occur during the entire life cycle of a product. In general these uncertainties are understood as deviations from the process and product properties. This fact makes it necessary to develop a comprehensive methodology for the analysis of uncertainties in the product life cycle, which is called Uncertainty-Mode- and Effects-Analysis (UMEA). It is a strategic procedure to analyse the uncertainties and their consequences. These uncertainties can be generated for example by different processes operations or by load changes of the product.
In planning and development processes uncertainties must be taken into account particularly in the modelling and forecasting of the technical, environmental and economic product and process properties.
The integrated Uncertainty-Mode- and Effects-Analysis methodology is based on a comprehensive life cycle model of uncertainty, which allows the consideration of uncertainties in all life cycle processes systematically, to describe and to evaluate the impact of uncertainties systematically in a standardized fashion.

Keywords: Uncertainty-Mode-and-Effects-Analysis (UMEA), methodology, process, product properties, product life cycle, FMEA, risk management

1 INTRODUCTION
Mechanical engineering products pass through different production and use phases during their entire life cycle. Uncertainties arise in all phases which are represented by a deviation around a fixed expectation value. These fluctuations are currently being compensated by tolerances. This general approach often guides to over dimensioning of components and products and finally to uneconomical products [1]. A precise differentiation of deviations in accordance with their variability and their origins and effects is necessary to avoid excessive size and defective behavior of products. These uncertainties are often caused by a lack of information and have to be reduced [2].
Uncertainty can be analysed in an integrated process model with the Uncertainty-Mode-and Effects-Analysis methodology (UMEA). This model serves as an application to capture and display uncertainties. The formation of uncertainties and the resulting effects are systematically collected in the generic process model and their propagation in process chains can be analysed with an effect-chain-model [3]. The underlying model of uncertainties in the UMEA is also the base for a comprehensive and consistent definition of uncertainty, a distinction comparable to concepts such as reliability, availability, error, risk or security.
The procedure is illustrated by an example of an airplane landing gear because this component bears large deviations in stress parameters, but for economic reasons it must be very light-weight.

2 PROPERTIES OF UNCERTAINTY
In the engineering sciences mainly uncertainties in materials and uncertainties in stress, including the mathematical collection of statistical deviations are considered [4]. Those are sophisticated and

demanding procedures of probability calculation. In the industrial application, however, reliability analysis is primarily performed qualitative and selective [5].
In the field engineering, there is no clear definition of uncertainty. Uncertainty is often associated with reliability, risk or tolerance [6].
The reliability analysis for nuclear power and in the geodesy, uncertainty is subdivided into two types: epistemic and aleatory uncertainty. In the epistemic uncertainties, uncertainty arises because of incomplete information and incomplete scientific knowledge. They can be reduced by more and new information. The aleatoric uncertainties come from the randomness of the process itself and can not be reduced further [7].
For uncertainty considerations are particularly relevant is the approach of Taguchi [8]. He considers monetarily asses losses arising from discrepancies with potential products for the whole of society and the arise of the entire product life cycle. Taguchi after this applies to all deviations of the functional properties of the targets [9].
The mathematic optimization of processes that deal with uncertainty is considered in the work of Li [10] for the salvation of optimization problems among the unsure boarder conditions and unsure model parameter. Linear and not linear, stationary and dynamic optimization problems among uncertainty are used for different optimization challenges in the industry. Especially in the stochastic and statistic, mathematic uncertainty is described and calculated [8], [11].
In the science of business administration uncertainty is mostly described by decision theory. Uncertainty will describe future environmental conditions, where no probabilities are available. Uncertainty is divided in the terms contingency, risk and ignorance [12]. At the term contingency, possible effects are known but there will be no information about the probability of occurrence. At the term risk information about the probability of occurrence are known, but not the exact date. When ignorance is the impact of alternatives not fully known. The decision theory offers a variety of methods for decision-making under uncertainty and risk [13].

2.1 Structure of the process model to analyse uncertainty

The process model of Heidemann [14] is established practically to model uncertainties in technical systems. Following the process model will display briefly just the possibility to consider uncertainty identification.

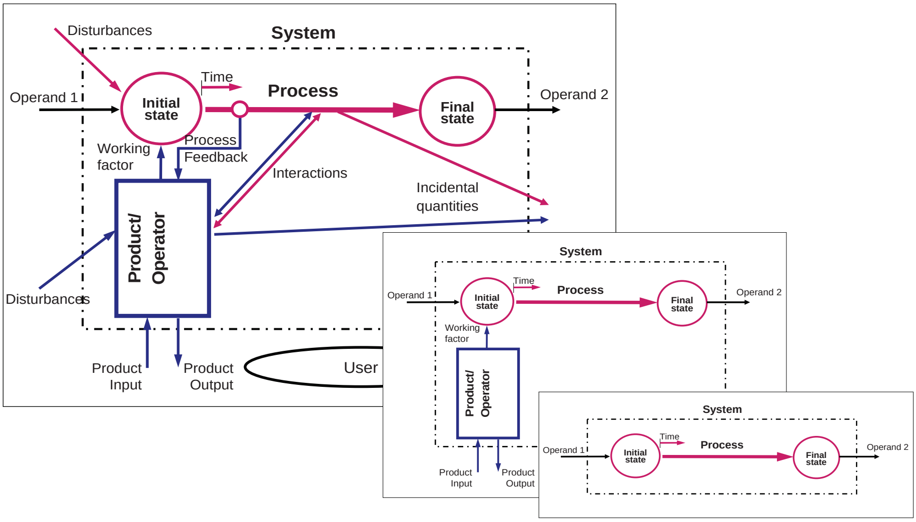

Figure 1: Complete, reduced and simple process model

Depending on the degree of detail in the product models, different properties of the process model can be used [15]. The complete process model includes the input and output variables and the labor resources, disturbance variables and interactions (Figure 1). For the actual process the operator (labor

resources/product) should be delineated between the production process and use process. The input and output variable is referred as operand. For identifying uncertainties in load-bearing systems in production, the occurring operands are mainly system elements (such as a piston rod of an airplane landing gear) which are edited during the process.
During the use process, the operand change into the operator (the aircraft landing gear is the operator which carries the plane as operand). The working factor refers to the connection between the labor resources/product and the initial state. Input variables (e.g. the electrical energy) and disturbance variables (e.g. ambient temperature) affect the labor resource/product. There can be interactions between labor resources/product and process. Additionally incidental quantities may emerge from the process (for example waste heat) and the product (for example sewage, noise emissions or lime scale. The simple process model is modeled without the labor resource and considers only input and output variables. It can be used in early stages of the development process.

2.2 Types of uncertainty in the model of uncertainties

When the process model is adapted to the specific conditions of life cycle processes of the product and process life cycle, different types of uncertainty can be detected. They are subdivided into aleatoric, epistemic and prognosis uncertainty (Figure 2) [16].

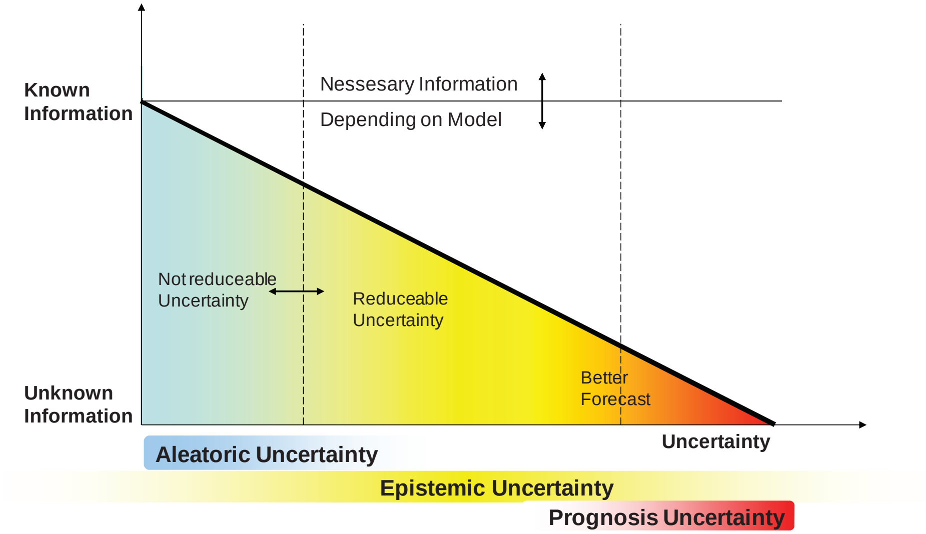

Figure 2: Properties of Uncertainty

Aleatoric uncertainty in the model of uncertainties

The process model by Heidemann for the production process in the product life cycle is shown in Figure 3. In those processes, the term "labor resource" is a general term for all components such as plant, machines or tools conditioning or processing applications. All process parameters are characterized by properties [17]. These properties have principle deviations from idealized properties. Additionally, external disturbance variables, incidental quantities and secondary variables, feedbacks like temperature fluctuation, corrosion or perturbing electric fields can cause a deviation of these process parameters.

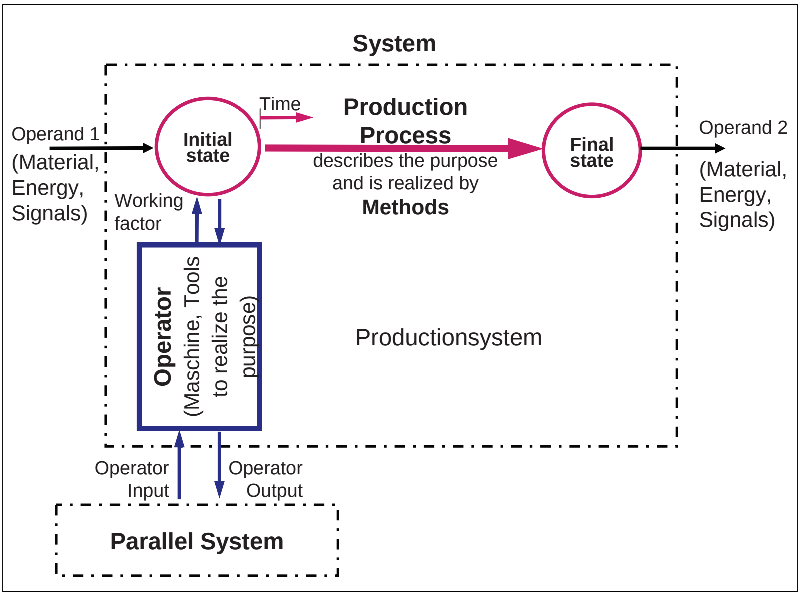

Figure 3: The process model for real production processes

In use processes the labor resource is replaced by the product. The special role of the use phase in the life cycle results from the fact, that the product is used as labor resource, while in the other stages of life cycle, the product will be operand [18].
A first approach to display virtual processes of planning and development in a customized process model shown in Figure 4.

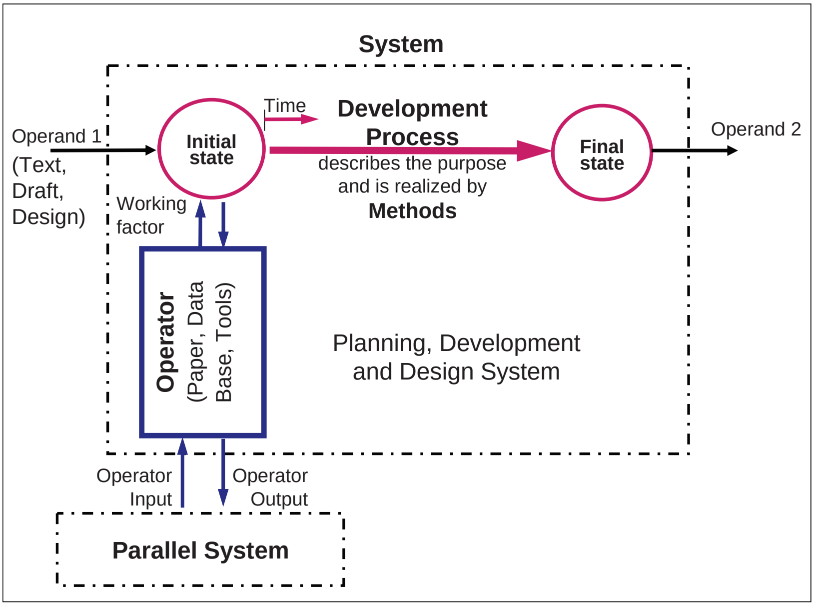

Figure 4: The Process Model for virtual planning and development processes.

In contrast to real life cycle processes, this process model data, information and knowledge are processed which leads to the term “virtual”. Aleatoric uncertainties (e.g. interface problems between different data formats or imprecise and ambiguous drafts versions for drawing parts) occour, similar to the real life cycle processes. Besides, disturbance variables, incidental quantities and feedbacks can cause deviations for example by unexact requirements or demotivate designers.
All these deviations are compliance with Taguchi aleatoric influences (e.g. influences caused by random deviations) [9]. For considering aleatoric uncertainties, there is an extensive number of statistic and probabilistic methods of the reliability and risk analysis. The key to a systematic identification of aleatoric uncertainties is a comprehensive process analysis with a generic process model.

Epistemic uncertainty in the model of uncertainties
Planning and development activities are based on ideas, assumptions, schemata or concepts, which can be subsumed under the term “model”. Models only represents a part of the totality of a real object. The quantity and precision of the model properties are limited compared to real object properties, which automatically causes epistemic uncertainties when working with models. For examples, during the simulation of an aircraft landing gear, there are uncertainties concerning the validity of the load application assumptions or uncertainties caused by numerical errors in calculation process.
The question of how epistemic uncertainties can be systematically collected or even considered for an uncertainty optimized product design, has not been answered yet and goes far beyond the approach of Taguchi. To estimate existing information and introduce experience can help to identify and reduce epistemic uncertainties. An approach for a systematic consideration of epistemic uncertainties is e.g. the pyramid model with its product models [15].

Prognosis uncertainty in the model of uncertainties
Product planning and development processes are always made for future operations and events, so a future time horizon has to be defined as a base for the design. At the moment, this aim has not been sufficiently achieved yet [19].
In addition to the time horizon, the use scenario has to be defined. In the design methodology, the task is clarified and the requirements list is compiled for this purpose. The forecast on future use scenarios is associated with high prognostic uncertainties. Also in this respect, the model clearly exceeds the approach of Taguchi which is basically limited to aleatoric uncertainties [9].
The prognosis uncertainty, which results from the time difference between virtual and real planning processes enhances with the time difference between the virtual individual planning and development phases (see Figure 5).

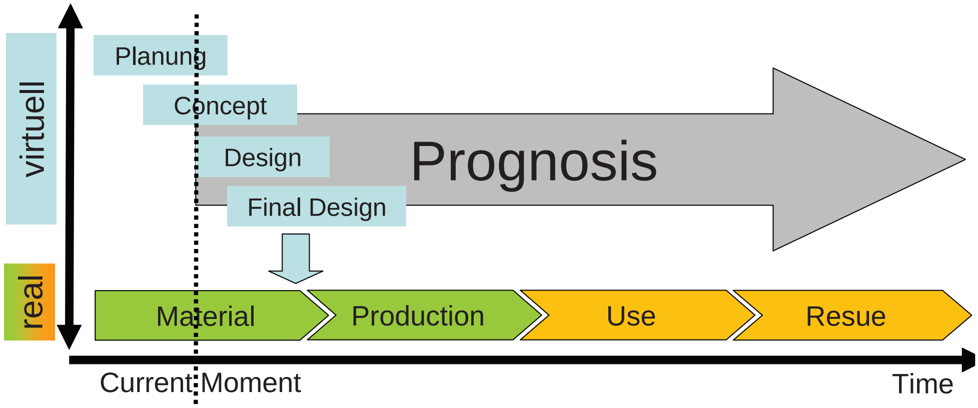

Figure 5: Prognosis of processes and properties in the product development

Product planning and development processes are always for future operations and events, a (later) time horizon take a basis for design [20].
As an example, the concept of a landing gear is fixed for earlier than the final product documentation. In the course of development can be initial prognoses (e.g. load assumptions, product conditions) in turn change, which causes future prognosis uncertainties.

3 GENERAL MODEL OF UNCERTAINTY

To illustrate uncertainties a special model of uncertainty is used which is supplemented by appropriate methods and strategies, to form a holistic uncertainty methodology. The model considers deviations in stress and strength of a technical system. It allows effects of these deviations in the process model to be analysed and to be described in the property- model. The calculation is implemented in matrices.

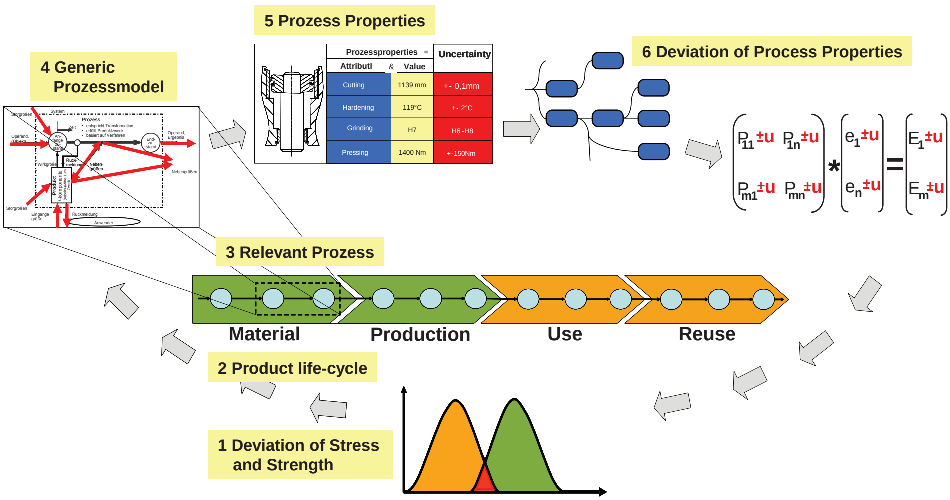

Figure 6: Concept of an model of uncertainties for the entire life cycle

3.1. The model of uncertainties includes the following sub-models:

1. The stress and strength is usually presented as deviation. Each distribution has an expectation value and a confidence interval that indicates the width of the distribution. The distance between the expectation values is now generally referred to as the safety factor [5]. If the expectation values of both stress and strength curves lie far apart and there is no overlap between the curves, there is no uncertainty in the model. An overlap in both curves represents the uncertainty. The uncertainty therefore results from the deviations of properties and property values.
2. The strength is determined in the early phase “material production” and “production” of the life cycle, while the stress occurs in the use phase of life cycle e.g. stress in aircrafts landing gear. Generally uncertainties occur in a certain life phase, but they can also be the result of influence during other life phases. In the stages “material production” – uncertainties can occur if the deviations are too high, before even reaching the use phase. For example, a hydraulic cylinder can no longer be mounted due to oversize. A holistic view of the entire product life cycle similar to the approach of Taguchi is required, to capture the general influences of uncertainty [9].
3. Looking detailied at the emergence of uncertainties in each phase of life, one can see, that uncertainties are linked to individual processes. Inhomogeneity of segregation for example plays an important role in the uncertainty of strength during the process “solidification of the melt”, when casting an aircraft landing gear component. For stress, extreme situations, such as

a sudden loading due to a hard landing with heavy load or a banking touchdown, are key design criteria. A differentiated uncertainty examination has to consider therefore at all relevant processes in the stages of life cycle.

4. If multiple processes during different phases of life are involved in the development of uncertainties, these processes have to be correlated with each other [14]. Just as there are processes, which increases uncertainties, there are processes, which contribute to a reduction of uncertainties. For example, a downstream process guide, an attached movable plunger or a seal with greater flexibility and could reduce uncertainties.
5. The strength of a technological system is a result of many material properties and properties of production. The specific stress caused by e.g. the process of landing. Object properties (e.g. weight), properties of the process itself or the chosen method (e.g. landing angle) and properties of the system environment (e.g. temperature) may be relevant. The generic process model must therefore be designed in such a way that all relevant factors, and effects or phenomena can be illustrated in its properties.
6. If the actual (observed or measured) process properties deviate from the ideal or planned value, this may lead to a different end process state or even a completely different process progression. An increasing of the notch effect on the landing gear due to corrosion or a incorrectly calculated strength of crosswind during the landing operation can damage or even break the gear. Uncertainty increases when the process properties deviate from the properties of the ideal process or when they cannot be determined.

Real product and process properties differ more or less heavily from the ideal value during planning and development processes and exhibit a stochastic distribution. A comprehensive model of uncertainty must therefore take distributions of properties into account.

A content founded structure of different types of uncertainties, an approach to model the propagation of uncertainties and their effects in the process chains and networks, as well as a process mapping of qualitative and quantitative methods for their identification, calculation and simulation, are illustrated in the model scheme. This classification model with the uncertainty definition is the base for the UMEA methodology in chapter 4 to identify, characterize, and estimate the uncertainty.

4 STRUCTURE OF THE UNCERTAINTY-MODE-AND-EFFECTS-ANALYSIS (UMEA) METHODOLOGY

The UMEA methodology is principally based on the generally applicable model of uncertainty (Figure 7). It covers both, simple and difficult problem definitions for methodical allocation throughout all life cycle phases.

The methods of the UMEA are selected in a way, that both simple and difficult problems can be solved effectively and efficiently and under consideration of all life cycle phases. For this purpose, a distinction is necessary between qualitative and quantitative methods, which differ strongly in their application. It is a theoretical approach and has to be evaluated in practice. The implementation of this UMEA-methodology is important but at the moment it is to early because the research has just started.

4.1 Classification of qualitative and quantitative assessments

The analysis of uncertainty in different stages of production development and throughout the entire life cycle and with varying requirements regarding to accuracy and expenditure, requires strongly differing methods.

A differentiation between the range of quantitative assessments and qualitative assessments is undertaken.

Qualitative assessments are particularly suitable in the initial phase of production development, when the requirements and current processes and properties are not yet fully defined in detail. A qualitative assessment of a system, with less information available, tends to be faster and promotes a better understanding of a system [21].

If an exact analysis is required, in which the optimization potential of the system or the process chain has to be determined among other things [22], then this is generally easier on the base of a quantitative model. The goal here is the illustration of a formalistic connection, despite uncertainties at which values of a model affect each other mutually.

4.2 UMEA methodology procedure

With the UMEA methodology a procedure for the determining and the containing of uncertainties is developed. The steps in this procedure are supported by methods. Alternative methods are assigned in every step. In the product development it has to be decided on a case-by-case basis, which respective method is appropriate for the problem and can be used. It is not necessary to do the whole analysis with each step for each new project, it depend on the experience of the person to skip some of them. When matching methods to the work steps of the UMEA, both well-known and less well-known innovative methods are used.

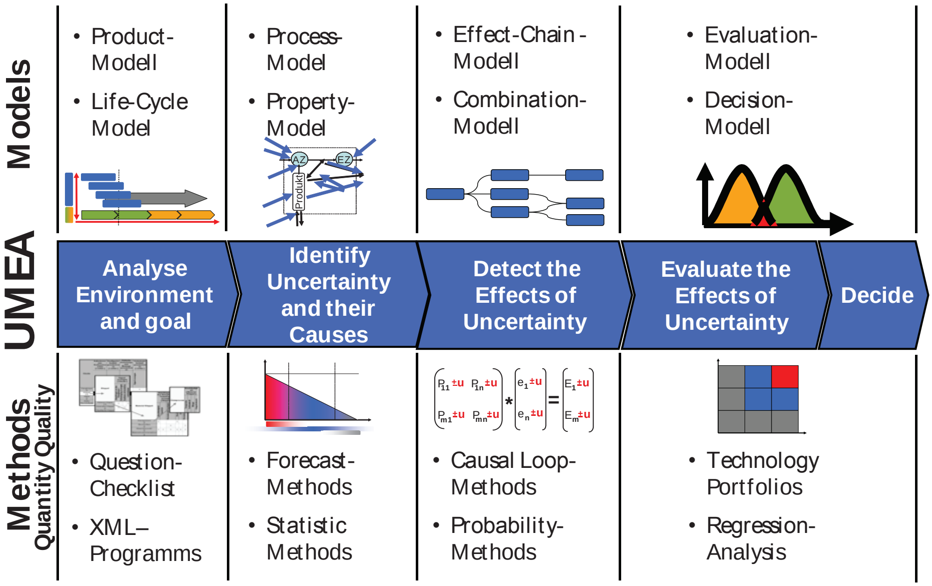

Figure 7: UMEA methodology procedure

The procedure of UMEA methodology is based on the methodical procedure of the risk management in business economics and is divided into a surrounding environment and a goal analysis, followed by the actual identification of uncertainties, the determination of effects of uncertainties as well as the evaluation and decision of the determined system uncertainty. The provided methods are described in the following chapters. The actual research is not far enough to say something about on what you have to know to be able to conduct the analysis methodology.

Methods for the environment and goal analysis

In the surrounding environment and goal analysis, a complete, comprehensive and systematic containment of uncertainties is undertaken [23]. This means determining a system border for the system in question in regard to the product life cycle, defining relevant neighboring systems, analyzing effects between the systems, as well as specifying evaluation bodies (e.g. user, stakeholder, requirement groups).

These evaluation bodies define dependent variables (e.g. minimization of the costs, the risk or the error rate and/or the maximization of the use or the quality) as well as the expected and tolerated border uncertainty. The border can shift, according to the development of technologies and market changes. An example is the standard equipment of airbag and ABS in small cars. During the mid-

1990's, these features would not have been expected by the buyer, nowadays the installation of these security properties are considered a standard, an absence would no longer be tolerated by the buyer.
For the surrounding environment and goal analysis, question lists are used for the analysis and definition of the system environment as well as checklists for the identification of products and processes with a pronounced uncertainty potential. These question and checklists can be derived from well-known lists and gradually supplemented and refined throughout the application of the UMEA methodology. Furthermore, possible evaluation bodies must be identified in markets, tolerated and border uncertainties derived from this information and transferred to the question- and checklists.

Methods for the identification of uncertainties and their causes

The identification of uncertainties describes all work steps required for the designation and description single uncertainties and their causes. For the actual identification of the aleatory uncertainties, a process analysis is conducted of the product lifecycle including the processing concepts according to chapter 2. The allocation of uncertainty-relevant process properties including the uncertainty which can be expected, is already done here.
In addition, identifying uncertainty includes the quantification of the uncertainty for the following calculation. The representation of the emergence and the cross-linking of different uncertainties can formally take place in the form of matrices, whereby processes, properties, and uncertainties can be represented in matrix arrays or vectors.
Nonetheless, there are ranges in which quantification is not feasible or meaningful and therefore uncertainty must be qualitatively described. This can be, for example in the early phases of the development process, during which a multiplicity of individual user behavior or complex systems cause the work required for quantification to stand in disproportion to the expected result. For quantification, also the type of the uncertainty must be specified similar to the systematics of the model of uncertainty.
For the identification of the different kinds of uncertainties and their causes, appropriate method classes, e.g. estimate methods, statistic calculation methods, prognosis instruments like the Delphi method, relevance tree analyses and CROSS-impact studies are selected. The precise method is selected in regard to an appropriate relationship between expenditure and attainable accuracy of the result.
Quantitative methods need a mathematical formulation of the uncertainty and its causes above all else. For this purpose, quantitative procedures of statistics and probability calculation are combined and prognosis instruments, such as linear and nonlinear trends as well as linear and nonlinear involution are used.

Methods for determining the effects of uncertainties

After defining the range of the uncertainty consideration and of the single uncertainties, the connection of uncertainties and their effects throughout process chains are regarded in this work step. The adapted effect chain model is used as a base. With this, uncertainties and effects can be cumulated to a system uncertainty and/or to a system effect. For the calculation, the calculation method must differentiate between qualitative and quantitative uncertainty types.
Effect chains are determined, using the effect chain model corresponding to the identified uncertainty causes within the regarded process chains. They qualitatively describe the propagation of the uncertainties and their effects on the product life cycle. This method can be refined further through an iterative approach using actual systems.
With quantitative methods, the possibility of a mathematical treatment of the cumulation of uncertainties arises [22]. For the possibilities of a calculation of the effects of uncertainties, cases of different levels of detail can be differentiated, for example simple mathematical optimization models which permit the determination of the system uncertainty. In the case of unevenly distributed deviations (e.g. due to empirical measurements) and complex linking of process chains and their uncertainty or effect categories (e.g. by modeling of a complete system over the entire lifecycle),
Boolean fault trees, Markov chains, probabilistic calculation methods or fuzzy logic present far more difficult mathematical obstacles. In particular the latter is only solvable in an acceptable manner after mastering the two preceding cases.

Methods for the evaluation of uncertainty and its effect

The evaluation of uncertainties is a comparison of the border values, recognized by the evaluation bodies with the system uncertainty determined by the uncertainty methodology in regard to the dependent variables defined before. The evaluation can take place by means of well-known and established evaluation methods.

Basic principles of the decision theory can be used for the methods of evaluation of the uncertainties and uncertainty effects. The approach here is the search of a solution to the decision problem by reduction of complexity.

Suitable methods must be examined regarding their applicability for the comprehensive evaluation of uncertainty. If epistemic uncertainties dominate, this can be accomplished for example by means of a method of intuitive evaluation e.g. a pair comparison. It can be used, if the knowledge of properties is incomplete or only some information trends are known [15].

In the case of aleatory uncertainties, mathematical procedures of statistics and probability calculation will be used above all else. In particular the SPC analysis, the Taguchi method, the Pareto analysis, hypotheses tests and the correlation and regression analyses are common here.

Epistemic uncertainties can be judged with the statistic decision theory. Optimal actions are specified as a function of sample information over environment conditions. The challenge here is the procurement of information for the purpose of making a decision despite uncertainty [9] [24].

For prognosis uncertainties, futurology methods (e.g. scenario technology) can be used. The descriptive decision theory tries to make true and as new statements as possible regarding reality and derive them empirically. [25]

Further methods are the product life cycle analyses, technology portfolios, Gap analyses, value analyses and the use of Fishbone diagrams. For the evaluation of the uncertainty, a balancing approach of the ecologic life cycle inventory analysis and effects can also be suitable [18].

Decision methods

The uncertainty evaluation is concluded with a decision-making process, because there are similar methods. The decision is based on well-known and proven methods. At present, there is no evidence that decision methods must be redeveloped or adapted. For the final decision, additional considerations in regard to person- and process-determined errors must still be taken into account [15].

4.4 Varieties of UMEA methodology

Based on the experiences with FMEA applications, it is to be expected that also the UMEA must be available in all varieties. Similar to the FMEA, it is anticipated, that the UMEA will be specialized in three varieties. For application in early development phases, a concept system-UMEA covers the entire product developing and use process.

It consists of the three, also independently applicable development forms: development UMEA, production UMEA and application UMEA. Based on the current knowledge level, the production UMEA and application UMEA are suitable particularly for the analysis of aleatory uncertainties in the product life cycle, whereas the development UMEA is particularly suitable for the analysis of epistemic and prognosis uncertainties.

Each UMEA variety consists of the same work steps for the analysis of uncertainties: environment and goal analysis, identification of uncertainties and their causes, determination of the effects of uncertainties and evaluation of uncertainties as well as judging their effects and making decisions.

The concept of the system-UMEA is first examined and refined using simple examples of active and passive frameworks. The holistic model of uncertainty is used and the results of the model systematics are compiled in a structured example collection. With an increasing number of examples, the result extent increases and can be used for comparisons, demarcations and clusterings of similar or particularly interesting phenomena. For example, many studies in the area of eco design show, that uncertainties in the range of consumer goods are particularly pronounced in the application phase[1].

Users of consumer goods are usually neither well instructed, nor will they usually strictly follow usage instructions. For the system UMEA this means that significant deviations must be anticipated between the planned and actual application process for the usage of consumer goods, which in turn has substantial retroactive effects on the uncertainties during planning and development phases.
Simulation tools that can be used for the mathematical description of the “propagation” of uncertainties and its effects are programs such as Modelica/Dymola and MathCad. The statistics and probability models assigned in the model of uncertainty must be linked appropriate to the according procedure during testing and refinement of the UMEA methodology.

5 CONCLUSION

For the analysis of uncertainties on the basis of the process model, it is shown how a holistic model of uncertainty can be adapted to depict the values and value distributions of particular properties.
The consolidation of the individual models to a holistic model of uncertainty permits a comprehensive and consistent description of aleatory, epistemic and prognosis uncertainties and their effects. The holistic uncertainty model furthermore permits a uniform description of uncertainties in all life cycle phases.
Building upon the model of uncertainty, a strategic approach was developed, which is divided into universally applicable work steps. The basic idea behind the methodical approach of the UMEA methodology, adapted from the FMEA is based on risk management in business economics.
For the analysis of uncertainties, a theoretical basic structure is created with UMEA methodology, with which it is possible to systematically determine uncertainties and their effects. In following studies, the UMEA must be further refined and tested for its practical fitness.
Due to the generic structure of UMEA methodology it is also possible to properly describe and analyse future technologies such as adaptronic solutions, whose properties in the utilization phase can change.

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