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UMEA - A FOLLOW-UP TO ANALYSE UNCERTAINTIES IN TECHNICAL SYSTEMS

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ABSTRACT

In mechanical engineering uncertainties occur during the entire life cycle of a product. These uncertainties are defined as deviations from process and product properties. This makes the development of a comprehensive methodology for analysing uncertainties necessary. The methodology is called Uncertainty Mode and Effects Analysis (UMEA) and consists of a strategic procedure to analyse uncertainties and their consequences. These uncertainties appear for example by different process operations or by variations during the utilization process 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 UMEA methodology is based on a comprehensive model of uncertainty, which allows the consideration of uncertainties in all life cycle phases to describe and to evaluate the impact of uncertainties systematically.

Keywords: UMEA, Uncertainty, Analysis, Development Process, Methods

1 INTRODUCTION

It is the aim of the Uncertainty Mode and Effects Analysis (UMEA) to show a methodological approach, to identify uncertainties and their causes clearly, to describe them standardized and to determine the propagation of uncertainties as well as their effects in process chains on downstream processes securely. Uncertainties in technical systems occur throughout the entire life cycle of a technical product. In general these uncertainties are defined as deviations from the process and product properties. This makes the development of a comprehensive methodology for analysing uncertainties necessary. This methodology is called UMEA. It is a strategic procedure to analyse uncertainties and their consequences. These uncertainties appear e.g. by different process operations or by variations during the utilization process of the product. The first step of the UMEA methodology procedure includes the definition of the goal [1]. In many cases uncertainties are caused by a lack of information and must be reduced [2]. This approach often leads to over-dimensioning of components as well as products and finally to uneconomical products [3]. The following work is based on the subproject A1 of the Collaborative Research Centre 805 (CRC 805), which is sponsored by the Deutsche Forschungsgemeinschaft. The research started in January 2009 and is not completed yet. The methodology is based on a consistent and comprehensive model of uncertainties for a systematic identification and description of uncertainties and their causes. This is done over the whole real as well as the whole virtual product life cycle. Furthermore, it should support and evaluate the effects of uncertainties in planning and development processes.

2 FUNDAMENTALS

2.1 Categories of Uncertainty

In technical load-carrying systems uncertainties are divided into three categories as defined by the CRC 805 (see Figure 1). According to the increasing state of knowledge about the deviations of the rated value of an uncertain product or process property, the three categories are: unknown uncertainty, estimated uncertainty and stochastic uncertainty [4].

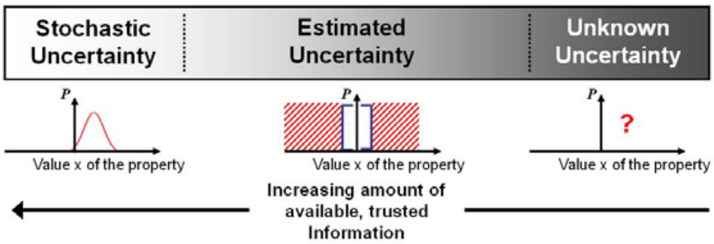

Figure 1. Categories of Uncertainty [4]

Unknown Uncertainty describes the situation that both the effects and the resulting deviation of a regarded property of uncertain processes are unknown. Based on this state of knowledge, no decisions can be made on the control of uncertainty. Unknown uncertainty often occurs in the beginning of product development when only little information about a future product is known and the product's properties are not determined yet.

Estimated Uncertainty describes a situation in which the effects of a regarded uncertain property are known. However, the probability distribution of the resulting deviation is only partially known. For example, this is the case when incomplete information about the expected properties of a product is known during the product development or if during manufacturing the product's properties are analysed randomly only.

Stochastic Uncertainty occurs when the effects and the resulting deviations of a regarded uncertain property are sufficiently (ideally completely) described by a probability distribution. Stochastic uncertainty is present after extensive analysis of properties in terms of quantifiable experiments and measurements.

2.2 Risk in Comparison to Uncertainty

Based on DIN VDE 31000-2 both Geiger/Kotte and Birkhofer define the terms safety and danger as areas of risk which are separated from each other by the tolerable risk whereas Geiger/Kotte speak of damage risk [5]. Hence there is a close link between risk, danger and safety.

To perform the distinction between safety and danger, the term risk has to be clarified. Therefore the notion of damage is needed. According to Birkhofer damage is referred to as an "impairment of the function of a technical product, […] and humans respectively the environment" [6]. For Geiger/Kotte damage is a "disadvantage from violation of legal interests arising from a technical process or condition" [5]. Even if the second definition is kept more abstract, both have in common that damage poses a negative impact to an element. The negative impact may be e.g. a personal injury, reputational damage or an economic loss [6]. After defining the notion of damage, now the definition of risk can follow. In technology risk is an evaluation quantity that provides information about the probability of occurrence of an unwanted incident (usually of damage) as well as about the expected damage degree upon the occurrence. The tolerable risk which cannot be detected qualitatively in general, designates "the greatest risk still justifiable of a specific technical process or condition" [6]. Now, safety is a specific area of risk. It describes a state where risk is lower than the tolerable risk. If risk is greater than tolerable risk, it is called danger [7].

In this context it is important to notice that in technology a state of absolute safety does not exist without any risk. Therefore risk is the measure according to which the distinction between safety and danger is drawn.

Examinations of uncertainties form the basis for examinations of risk. Examinations of risk complete the examination of uncertainties via an evaluation of the consequences ("evaluation level"). Finally examinations of risk form the basis to make a decision. Uncertainty in general is used in a broader scope than risk. It leads to a differentiated statement about causes and effects of process variations (Figure 2). The methods from the risk theory can be used for the evaluation of uncertainty.

Figure 2. Risk and Uncertainty

2.3 Reliability in Comparison to Uncertainty

Reliability in engineering is according to DIN 40041 the property or ability of a unit (process, product, person, system) [8], to satisfy its requirements during or after the specified time limits. This means that reliability during the operation of a technical system is equal with non existence of failures, i.e. one does not expect failures of functions or components [9]. Furthermore DIN EN ISO 9000 describes reliability as a “summing up term to characterize the availability and their influence coefficients, functionality, maintenance, supportability” [10]. To describe or to determine reliability, the failure probability respectively the probability of survival is used.

2.4 Model, Method, Methodology

The UMEA methodology consists of models and methods. The following description shows the difference between the definitions.

A model is a simplified abstract, purposeful structure and should comply with certain requirements. It should present the best possible image of the real world and mainly provide useful insights about the object of interest [11]. It should be as complicated as necessary and thereby as simple as possible.

A method represents an instruction that processes input to output parameters and thereby supports, for example decision-making, development or evaluation processes [6]. According to Lindemann, a method is characterised by several features [12]. Methods provide a prescriptive, goal-oriented and mainly rule based approach. They are a prescribed formalism for the focused solution of a problem. Furthermore a method is characterised by its operational nature. In praxis the concept of methods is not always clearly definable. For example, techniques which consist only of a few action sequences are also referred as a method such as combinations of methods (also called meta-methods) which consists of several individual methods.

A methodology is a procedure for achieving a specific goal, where models and methods are used and methods in general to planned procedure to achieve a specific goal [12]. In this connection methods as well as strategies, e.g. Simultaneous Engineering, tool, e.g. checklists or forms, and other resources are used. A methodology is a procedure plan which consists of multiple models and methods [2].

3 MODEL OF UNCERTAINTY

In the early phase of the product development process, a relative simple model of uncertainty (Figure 3a) can be used. Here, a nonlinear relationship between information and uncertainty is assumed, where a low degree of information leads to a high level of uncertainty. The curve approximates the axis asymptotic, because the states of complete ignorance (no information and the highest degree of uncertainty) and the state of complete information (no uncertainty) never exist in reality. At this time of the development it is still the process of requirement determination, in which a lack of information still dominates [13].

Later in the product development process it makes sense to use another model of uncertainty because of the higher level of information at this time. As shown in Figure 3b there is a differentiation between aleatory, epidemic and forecast uncertainty [13].

In the last phase of the product development process another model of uncertainty is used (Figure 3c). It is the model of uncertainty developed in the CRC 805 (see chapter 2). This model divides uncertainties in a more detailed way as it is necessary in the final development phases.

Quantification of information: For the calculation with uncertainties the underlying information about the uncertainty must be quantified. In many cases an adequate mathematical description of the real information by means of real numbers is not possible. This holds mainly if there is only a vague characterisation of the corresponding parameter or if there is only incomplete information about the parameter. Therefore, fuzzy sets were introduced by Zadeh in 1965 [14]. In classical set theory an element either belongs or does not belong to the set. In contrast fuzzy sets permit a gradual assessment of the membership of elements in a set. This is described by a membership function valued in the real unit interval [0,1]. Specialisations of fuzzy sets are fuzzy numbers. A fuzzy number refers to a connected set of possible values, where each possible value has its own weight between 0 and 1. With this states from unknown uncertainty (everything is possible, nothing is sure) over estimated uncertainty (everything between a lower and an upper bound is possible) to complete information (arbitrary possibility distribution or a special case a real number) can be treated [15]. An extended arithmetic was introduced for the computation with fuzzy numbers [16]. Therefore, object of further research will be the extension of methods used in the UMEA to the fuzzy arithmetic.

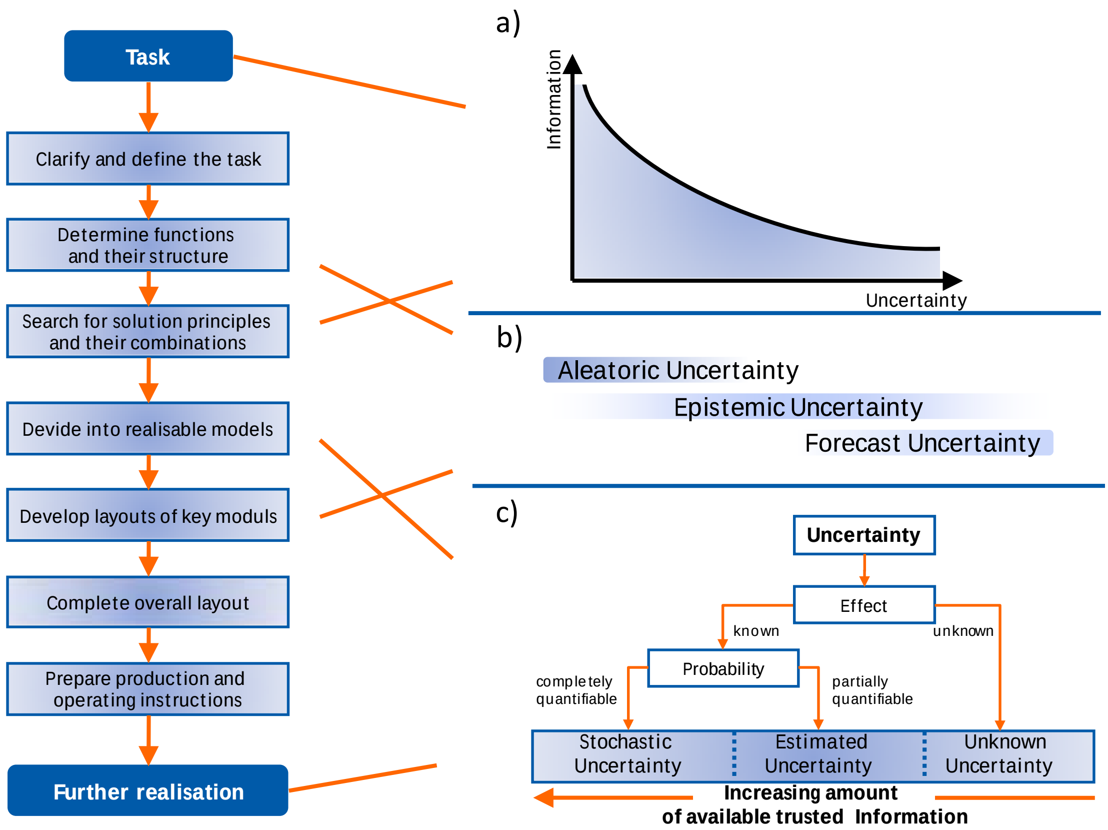

Figure 3. Models of Uncertainty assigned to the Product Development Process

4 UMEA

The approach of the UMEA is based on the risk management process in business economics. In literature risk management is often seen as a process whose execution is mostly subdivided into four steps [17]. According to DIN IEC 62198, risk management is understood as the "systematic application of principles of management for the purpose of finding out the context as well as identification, analysis, evaluation and controlling/management of risks". As the UMEA only tries to analyse uncertainties, the last step which is assigned for controlling and measures against uncertainty is not necessary. This step will be executed by the separate robust design methodology which is based on the results of the UMEA [18].

4.1 Work steps of the UMEA

The UMEA methodology persists of 4 work steps: First there is 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 (see Figure 4) [1].

Environment and goal analysis: In the first step of the UMEA a detailed and systematic investigation of possible uncertainties is performed. For this, the object to be examined has to be differentiated as a system from its surroundings in order to determine the influences of other systems and objects (adjacent systems, but also product user, etc.). In addition evaluation bodies (e.g. user, stakeholder, requirement groups) are specified. These evaluation bodies define dependent variables (e.g. minimisation of the costs, the risk or the error rate and/or the maximisation of the use or the quality) as well as the expected and tolerated border uncertainty.

Identification of uncertainties and their causes: In this step relevant uncertainties and their causes must be designated and described. Thereby relevant means, that the uncertainty of a process or product property has an influence on the dependent variable. If quantification is possible, it is done here to allow a calculation in the following steps. The detected uncertainties and effects are cumulated to a system uncertainty and/or to a system effect.

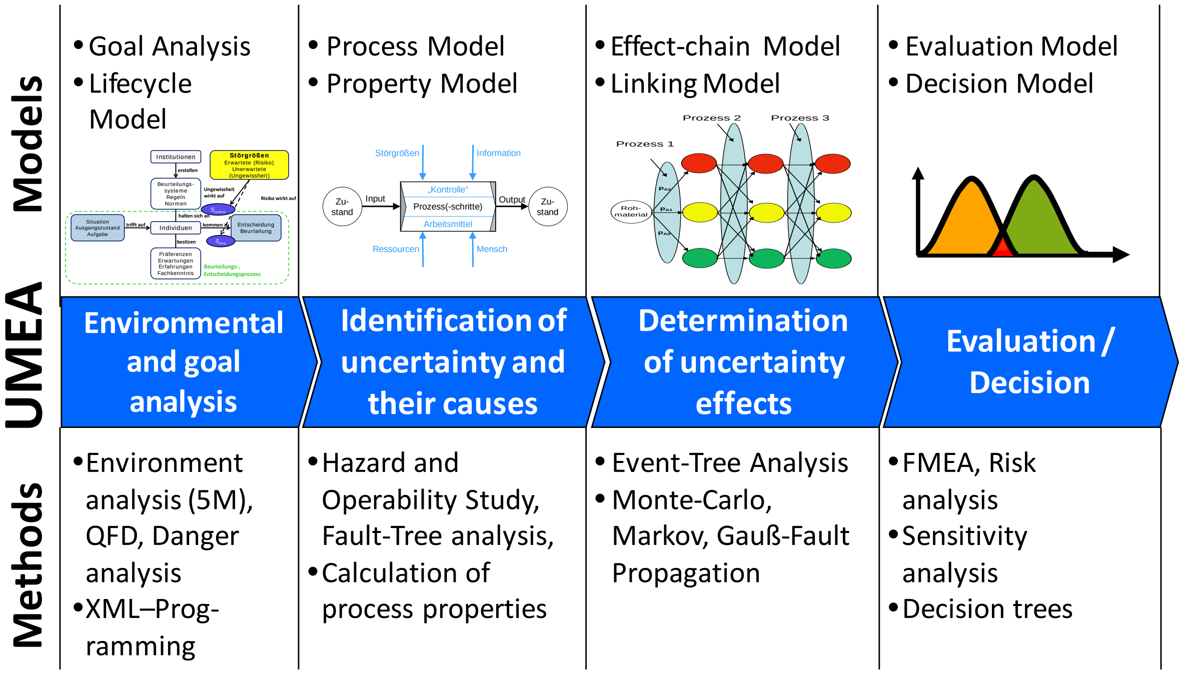

Figure 4. The UMEA Methodology [1]

Detection of effects of uncertainties: After the single uncertainties are determined, the connection of uncertainties and their effects throughout the whole process chain are calculated in this work step. The attention is also turned to the impact of the single uncertainties to the whole system which was defined in step one.

Evaluation of uncertainty effects and decision: In the fourth phase the previously identified and analysed uncertainties, along with their effects, are assessed and evaluated in order to establish a basis of decision-making for further measures, for example to prevent and to reduce uncertainties. Here, the uncertainties with their characteristics have to be compared with the previously determined objectives from the environment and goal analysis. The UMEA is completed with the decision step where one of the alternatives from the previous step is chosen.

4.2 Assignment of Models to the Phases of the UMEA

In this chapter the models of the UMEA phases are explained.

Environment and goal analysis: The focus of our new developed model for the first phase is the decision maker, who has to evaluate an initial situation (Figure 5) [20].

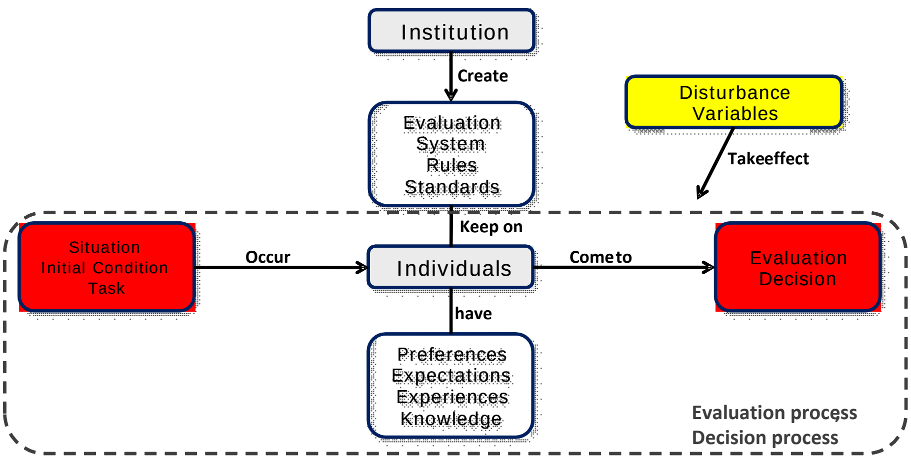

Figure 5. Model to Analyse Environment and Goal [20]

This can be an individual as well as a group of people. This decision maker has a personal component peculiar to him, in the following called personal preference. It ensures that two appraisals under the same conditions can lead to different results. This component includes experiences, preferences, technical knowledge and expectations. These are individually different and can change permanently (not constant).

On the left side the initial condition can be seen. It shows the alternatives or processes before the evaluation. On the right side the result of the evaluation can be seen, thus the evaluated alternatives and processes. Around these four components a system boundary is drawn, so that the remaining components take effect from the outside of the system.

The most important components are the previously already mentioned evaluation institutes. This includes all institutions which are known by the decision maker. He will not include other, unknown to him, institutions in his evaluation process. These institutions create a, commonly known as evaluation system (rules, standards) which is used by the decision maker for his orientation.

A second important external variable are the disturbance variables. They can be classified into known and unknown disturbance variables. Disturbances occur from an economic view often in form of asymmetric information.

Identification of uncertainties and their causes: The process model by Heidemann [11] for the production process in the product life cycle can be used in the second phase (Figure 6). In those processes, the term "labour resource" is a general term for all components such as plant, machines as well as tool conditioning or processing applications. All process parameters are characterised by properties [19]. These properties have principle deviations from idealised 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.

In use processes the labour 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 labour resource, whereas the same will be operand [19].

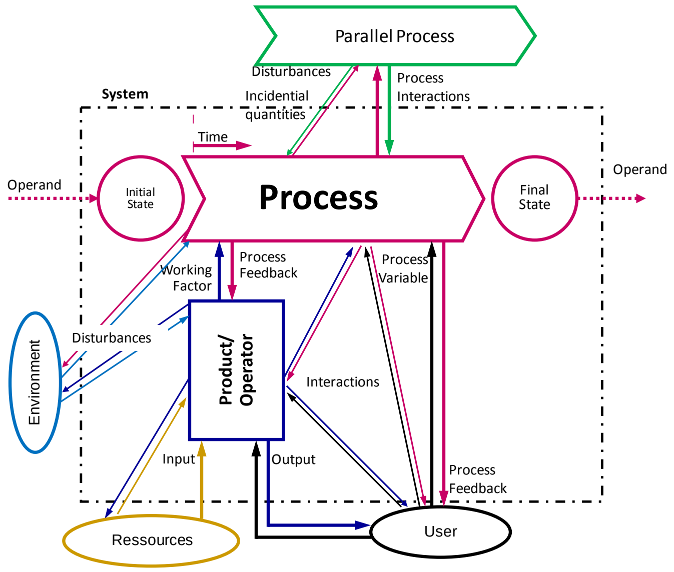

Figure 6. Process Model [19]

Uncertainties are also caused due to the deviation of the behaviour of work equipment and they affect the properties at the end of the process. Non-linearities such as thermal expansion, flexible deformations or compressibility cause uncertainties frequently. For example, the drill dust can damage the drill.

Detection of effects of uncertainties: The analysis of production or use processes by means of a process model usually reveals a broad range of influencing factors. While resulting from the input properties, the process, disturbances etc., uncertainty thereby can be caused not only by a single influence but by combinations and interactions between them. Extended to the whole process chain, an analysis additionally needs to account for relationships between processes, the accumulation of uncertainty, etc. Altogether, this results in a highly complex analysis that cannot be effectuated with reasonable effort in practice. An integral part of the UMEA methodology therefore is a model of the underlying cause-effect relationships.

Two Examples of existing approaches for the analysis of process structures are cause-effect relationships from the field of EcoDesign and stochastic Markov Chains. Based on methods, such as ETA, FTA, etc., Oberender [20] elaborates an effect-chain to identify product properties that could impair the environment in use processes (see Figure 7). With the help of Markov Chains the evolution of a system in time is analysed. By the definition of the probability for a change of state, different production steps can be modelled [21].

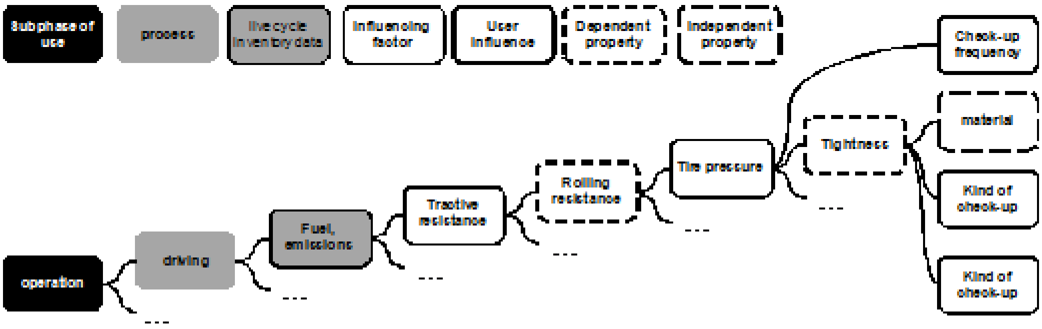

Figure 7. Cause-effects of a tire [20]

For an analysis of uncertainty, both approaches have drawbacks. Oberender only analyses the hierarchical relation between processes and product properties. Interactions between variables and the resulting impacts are neglected. In this way, key drivers for an impairment of environment can be identified, whereas the complex relationships of uncertain influencing factors cannot be indicated. The great disadvantage of Markov Chains is their memoryless property. The change in state only depends on the actual one, so that influences of uncertainty on later processes could not be modelled. For these reasons, currently an extended effect-chain model is elaborated within the CRC, based on a detailed analysis and classification of production and use processes as well as the analysis of product properties. The aim is a goal-oriented examination of cause-effect relationships in process chains that can also serve as a basis for a quantitative analysis.

Evaluation of uncertainty effects and Decision: Due to its comprehensive nature, a Risk Model can show all aspects of the uncertainty analysis. As a description model for risk, the Zurich Hazard Analysis Matrix (ZHA) has been established. The matrix combines the level of uncertainty and their effects. In all phases of the product development process it is possible to determine risk causes by uncertainty [22].

4.3 Assignment of methods

The results of the assignment of methods are shown in Figure 8. Because of the huge number of methods they are not explained in detail. Included in our list are all the methods which are conform to requirements in UMEA phases. In the case that less than five methods are conforming, also the methods with a partial conformation of our requirements were classified. In general, an assignment of methods to the phases of the UMEA is possible and to each phase methods could be assigned. Even if in the first phase only qualitative methods could be assigned. However, from the beginning it was anticipated that not every method can be applied at each phase. For example a method to identify uncertainties is only in the minority of cases also capable to evaluate these uncertainties. Furthermore there are methods, e.g. the Delphi method and FMEA, which can be, due to their thickness, used completely or partially in different phases. Likewise, there are methods like the ZHA that can be applied qualitatively as well as quantitatively. Whereby under a quantitative method we understand a method that makes use of procedures and methods from statistics and probability theory. The Delphi method can be, due to its exploratory character, used for an environment and goal analysis as well as to identify uncertainties und their effects. Also the results of the ZHA, which can during its performance identify and evaluate uncertainties as well as effects, can be used in several phases. However, there are also “expert methods”, which only can be used in a single phase, due to their specific character e.g. the event tree analysis (ETA), which is predestinated to determine effects of an event (an uncertainty). Once there is enough information for the quantification of uncertainties, methods like interval analysis, Monte Carlo simulation or sensitivity analysis can be used to compute the effects and propagation of uncertainties through the whole process chain.

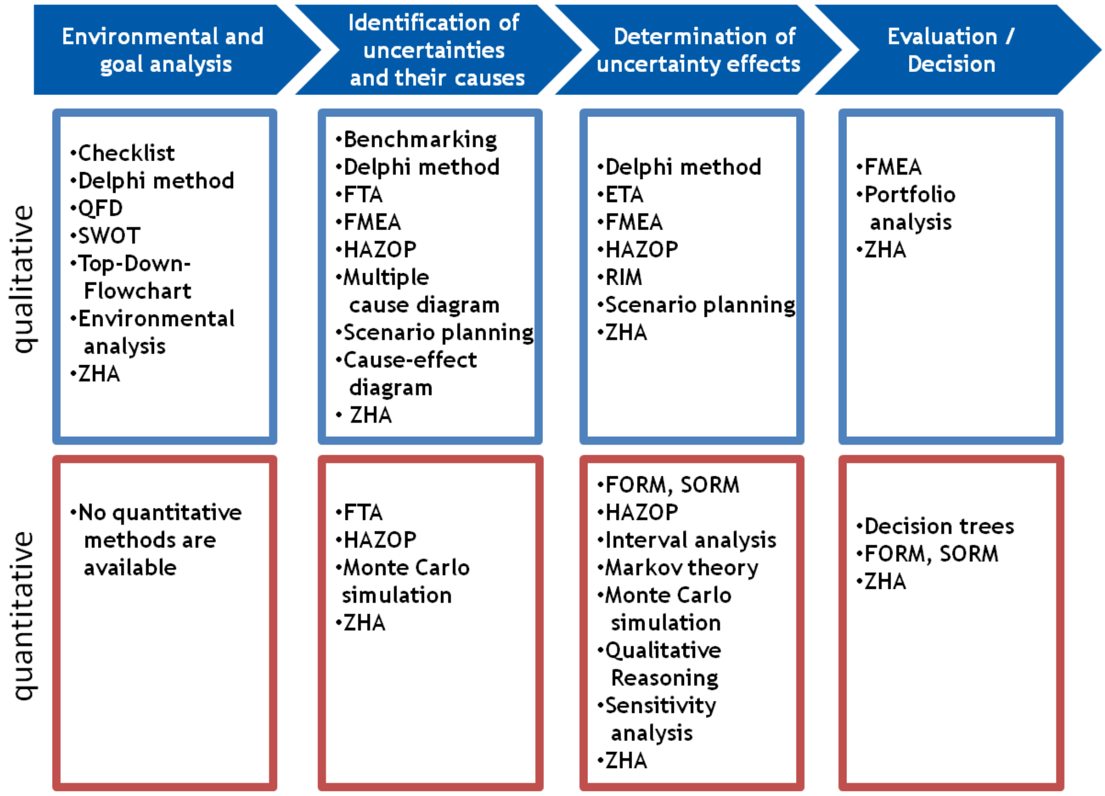

Figure 8. Assignment of qualitative and quantitative methods to the work steps of the UMEA

Another result of the assignment of methods can be seen by the fact that not all methods satisfy all requirements of an UMEA phase. For example, portfolio techniques are highly qualified to demonstrate uncertainties with their probability of occurrence and degree of effects, and to put them into a priority order. In contrast they are not qualified to attach values to the effects of the uncertainties. These values are necessary, for example, for an application of a risk portfolio. Therefore at least one supporting method is necessary. The same applies for the Quality Function Deployment (QFD) method, which includes the evaluation institute "client" into the goal analysis. But other evaluation institutes are not captured by it. The consequence of this is that the associated methods have to be, depending on the situation in a UMEA phase, supported by other methods, because some methods are highly qualified for a specific application.

5 EXAMPLE

Selected methods will be linked to a chain of effects along the UMEA phases for analysing uncertainties exemplarily (Figure 9). Here, the methods are not always used as a whole. In some cases, a modular approach of the methods is done. So only those elements are applied, which are useful in the combination of the particular UMEA phase. During the connection of the methods, the compatibility was guaranteed by the investigation of interfaces of the several methods and their sub-phases, respectively if the output of a method generally could be a possible input for following methods. This formal aspect is a necessary condition for the combination of methods. This degree of

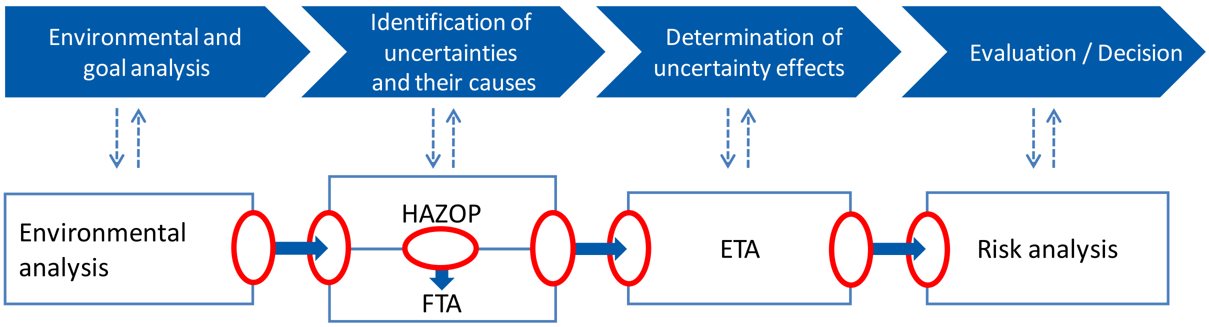

Figure 9: Example of linking methods

performance is a sufficient condition for the possibility of connecting methods and guarantees that the whole connection is conclusive in itself and reflects the requirements of the UMEA. To take the specific uncertainties of the life cycle process into account, the sequence of analysis steps, demonstrated in Figure 9 is possible. In a first step an analysis of the environment (e.g. QFD) is performed. After the definition of a system boundary, the QFD method provides a classification of the environment into parts of customer and technical requirements.
Considering their results, the environment analysis is followed by the Hazard and Operability Study (HAZOP) analysis. The relevant process parameters will be systematically linked with the HAZOP analysis specific keywords and the connection interpreted as defined by the task. The result of this step is a variety of uncertainties, for which yet no reasons are available. At this time a classification of uncertainties into stochastic uncertainty, estimated uncertainty and unknown uncertainty and consequently a preliminary prioritisation is already possible. Therefore, in order to analyse the causes of uncertainty, a FTA has to be performed afterwards.
In the third step the consequences of these analysed uncertainties are taken into account. This can be done by the Event Tree Analysis (ETA), which uses logical processes to evaluate event tree sequences and quantify the consequences. The question concerning the consequences of a possible uncertainty is answered by the QFD in the first step.
According to the method of risk analysis, an assessment of the level of uncertainties and their effects can be done. This is the last phase in the UMEA methodology.

6 CONCLUSION AND FUTURE WORK

By means of the UMEA methodology, uncertainties in technical systems can be analysed and evaluated. By means of the used models, the uncertainty can be represented in the UMEA phases. Methods which are appropriate for the UMEA were chosen. To combine the methods, interfaces were designated, which are required for the formal compatibility of the connected methods. It must be emphasized that depending on the current level of uncertainty appropriate methods have to be chosen. Even if there is much information about the uncertainties it must not be taken for granted that also all relations and relevant factors can be described by stochastic means. Therefore a combination of qualitative and quantitative methods is necessary for a comprehensive uncertainty analysis. But this is a challenging task and object of future work. In more complex systems and for the suggested combination of methods it becomes obvious that a great amount of work is required for the UMEA. In the following a software supported system of the analysis should be introduced. Methods of the different UMEA phases where linked in Excel to get a first impression of the working procedure. By means of practical examples (using the CRC demonstrator of a buckling rod structure and a hydraulic cylinder) an evaluation of the UMEA will be done. The assignment of combination methods to the phases of the life cycle of a product is subject of further research. Future investigations could resume the analysis of the interfaces particularly in regard to automated parameter transfer between linked methods.

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