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LINKAGE OF METHODS WITHIN THE UMEA METHODOLOGY - AN APPROACH TO ANALYSE UNCERTAINTIES IN THE PRODUCT DEVELOPMENT PROCESS

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ABSTRACT

In its entire life cycle every product is exposed to different uncertainties. In technical systems, these uncertainties are generally understood as deviations from nominal states of product and process properties. In development processes uncertainties particularly occur when modelling and forecasting technical or economic product and process properties. The Uncertainty-Mode- and Effect-Analysis (UMEA) Methodology forms a strategic procedure to analyse uncertainties and their consequences. The Objective of this paper is to show the use of methods within the UMEA Methodology during the phases of the product development process. In doing so uncertainties are recorded and described systematically at all virtual and real life cycle processes. In order to implement the UMEA, methods were allocated to different phases of the product development process. As shown in the following, particularly in their combination and interlinking these methods allow the detection and evaluation of uncertainties.

Keywords: uncertainty, UMEA, process, properties, methods, model

1 INTRODUCTION

The concept of uncertainty has a wide scope. Uncertainty in engineering systems includes all deviations that are caused by process properties (e.g. the effects of temperature) and variations in product properties (e.g. a modified shaft diameter). Uncertainties occur in processes and reproduce in properties [1]. In practice, one tries to control uncertainties with the help of safety factors. In general, this leads to over-dimensioning of components and often to increasing costs. Especially in the early phases of the product development, decisions must be made that have varying degrees of impact on the future product. The objective is to identify suitable methods for the analysis of uncertainties and in doing so to show the use of methods within the Uncertainty-Mode- and Effects-Analysis (UMEA) [2]. In early stages of the product development the level of knowledge of a future product is very low. Additionally, a high degree of uncertainty exists with respect to the expected processes and their properties. In real products and production processes, uncertainties exist in the form of (i) varying output variables regarding product properties or (ii) in various processes of use. In the field of product development, especially the prediction of uncertainty and variability is still under-represented.

The analysis and classification of uncertainties is largely used in the field of business administration, particularly within the decision theory. With the growth of information, uncertainty may change its state. When describing alternatives of action, potential environmental conditions play a major role. A decision under the assumption of a particular environmental condition is not equivalent to the same decision under the assumption of another environmental condition [3]. The range of different classifications reflects the different classification of uncertainties that can be summarized in models.

2 UNCERTAINTIES IN THE PRODUCT DEVELOPMENT PROCESS

Uncertainties in the product development process can often be described by the information level of the product that is to be developed [4].

In literature uncertainties are described by different models. These models differ in their point of view and their goal, the technical aspect is insufficiently reflected.

Morgan and Henrion define uncertainty as a part of risk analysis [5]. Other definitions can be found in Knight, who distinguishes risk and uncertainty within the context of decision theory [6]. In case of uncertainty a decision will be concluded without the use of mathematical probabilities but in case of risk the decision will be based on them.

Further current classifications of uncertainty and definitions are described by the authors Thunnissen and Radner [7], [8]. All these models of uncertainty and classifications come from the field of economy and mathematics. In the technical field and especially in product development there have been studies about these classifications from e.g. Chalupnik and de Weck [9], [10].

In the technical field different uncertainties can be distinguished. Uncertainties in models, calculations, measurements or processes are of high importance. Uncertainties which are investigated in data, parameters or inputs are of second importance [11].

Disregarding these classifications, uncertainties are classified into the categories of aleatoric and epistemic uncertainties. Moreover the new category “Prognostic Uncertainties” is introduced [2].

Aleatoric uncertainties are based on a random variation of cause variables and they are of stochastic nature [12]. For this reason aleatoric uncertainties cannot be reduced or eliminated by a higher degree of information. Epistemic uncertainties can occur for instance due to model simplifications, measurement errors or a small number of measurements. Independent of the information level, a residual uncertainty remains which is of stochastic nature [13]. The prognostic uncertainties occur due to a temporal difference between the virtual and the real planning and the development process respectively [11].

In summary, out of the different definitions of uncertainty the model of uncertainty can be established. This model provides a reasonable classification of uncertainty properties due to *(i)* effect and probability as well as to *(ii)* the categorization according to unknown uncertainty, estimated uncertainty and stochastic uncertainty of processes (see Figure 1). Based on a decision tree, the present uncertain property can be assigned to one of these three classifications. This uncertainty model was developed in the Collaborative Research Centre 805 (CRC 805) [14].

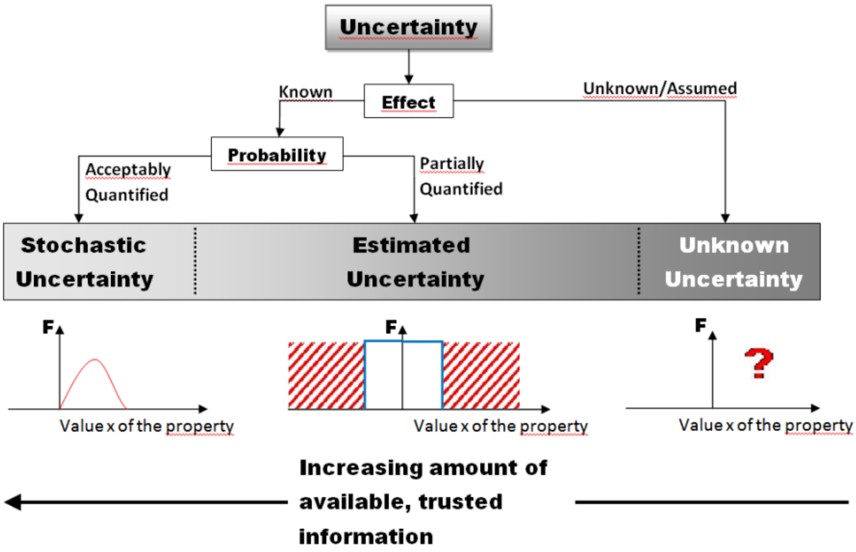

Figure 1: Model of uncertainty [14]

Uncertainties are distinguished in three categories by the increasing awareness level of the probability distribution which is related to a value of an uncertain property of a product or process: unknown uncertainty, estimated uncertainty and stochastic uncertainty.

1. In **stochastic uncertainty** effects and resulting divergences of a considered uncertain property are sufficiently (in ideal case entirely) defined.
2. **Estimated uncertainty** describes a situation in which effects of a considered uncertain property are known. However, the probability distribution of the resulting divergences is partially available.
3. **Unknown uncertainty** describes a situation in which both effects and resulting divergences of a considered uncertain property are unknown. Based on this information level, no decisions for uncertainty control can be made.

A tight classification of the three categories cannot be made; there is no clear dividing line. In general, an increasing amount of available and solid information results more and more in a stochastic uncertainty.

3 UNCERTAINTY METHODOLOGY AND PRODUCT MODEL

The Uncertainty-Mode- and Effects-Analysis is developed to determine uncertainties in technical systems (Figure 2). The approach in the UMEA is based on the risk management process in business economics [2]. In this context it uses models and methods which can be applied mainly in the technical field. The UMEA is divided into five steps, whereby each step is supported by models and methods of quantitative as well as qualitative nature.

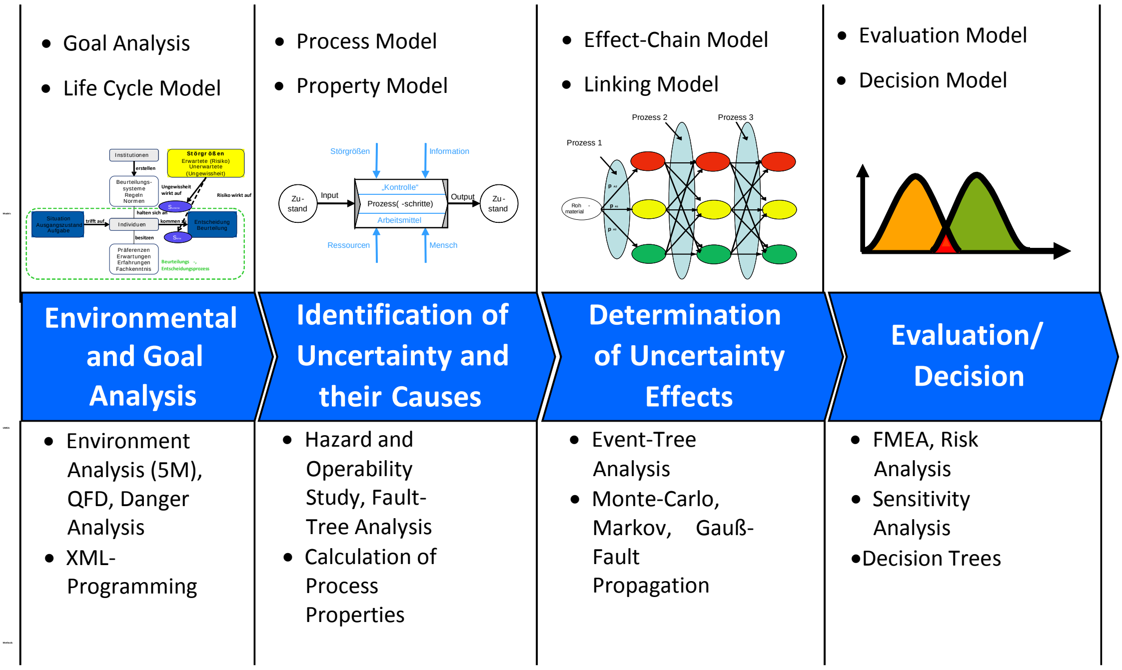

Figure 2: The Uncertainty-Mode- and Effects-Analysis [2]

Here, the qualitative methods should be applied particularly in the first steps of the product development, as long as requirements and properties for the product are not fully defined. A precise analysis which points out exact potentials for improvement certainly can only be achieved by quantitative methods with statistical values [11]. The methodology is classified into the following steps: Objective- and environmental analysis, identification of uncertainties, determination of effects of uncertainties, validation of uncertainties and decision making.

In the first step of the UMEA, the goal and environment analysis, a complete and systematic investigation of possible uncertainties is performed. For this purpose the examined object is differentiated as a system from its environment in order to determine the influences by other systems and objects (adjacent systems, but also product user, etc). In the first step checklists and questionnaires can be an initial suggestion for methodical support. In the next step all uncertainties, including their possible causes, are to be identified. For this purpose for example the Delphi-method can be applied. After identification and before evaluation or assessment, in a next step the detected uncertainties have to be investigated in their linking or assessment. In all steps a case-by-case decision has to be made in order to find out which methods are sensibly applicable [4]. Different methods must be used in order to apply the UMEA methodology in product development.

This classification of methods is based on the pyramid of the product models (Figure 3) [15]. The pyramid of the product models consists of four levels and represents the product development process. The models represent the work results of each step within a product development process. The pyramid's shape indicates on the one hand the possible range of variants and on the other hand the increasing number of defined product properties. Furthermore, at each level an alignment with the requirements is carried out. The results are verified with the requirements and new requirements are defined on the basis of the results [16]. In early stages in product development many decisions of high significance must be made. Usually those are subject to significant uncertainties regarding the product itself as well as to the development and manufacturing process.

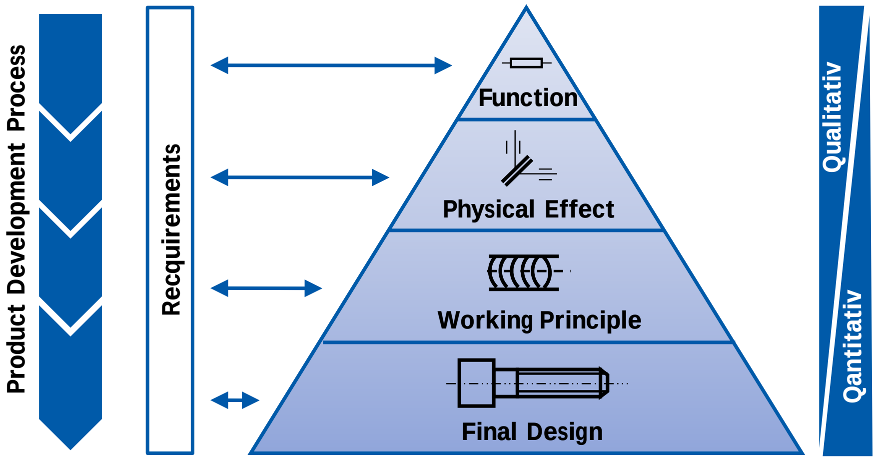

Figure 3: Pyramid of the product models [16]

Furthermore, at each level an alignment with the requirements is carried out. The results are verified with the requirements and new requirements are defined on the basis of the results [16]. In early stages in product development many decisions of high significance must be made. Usually those are subject to significant uncertainties regarding the product itself as well as to the development and manufacturing process. Based on the presented Uncertainty-Mode- and Effects-Analysis, uncertainties in the development process can be identified and assessed. Consequently, relevant processes and process properties which should be considered during the development can be identified. In advanced phases of the product development process as well as in the product lifecycle, uncertainties occur which can be analysed and eliminated by the UMEA [2].

4. METHODS FOR THE UNCERTAINTY ASSESSMENT DURING THE PRODUCT DEVELOPMENT PROCESS

An assignment to a certain method can be made when using results obtained during the early stages which are concerning the level of information as well as the properties. Particularly in the early stages, methods should fulfil the following properties: [17]

- low application of resources: method must not cause large costs
- individual activity (little teamwork): method must be easy to use
- high degree of uncertainty and little information: method must be able to deal with little information

Especially the latter property once again backs the previously derived coherence between the level of information and the earlier respectively later stages of product development. Inherently, assigning a certain method to the product development process is possible. However, it depends on the situation.

It can be ascertained that qualitative empirical tools should be preferred during the early stages, since in many cases no statistical data base exists. The latter would be a requirement for quantitative methods. In early stages the product is not specific yet. Thus, the corresponding manufacturing processes are not definite either. If these are known in later stages, statistical values are used to identify uncertainties. This can be realized with the help of quantitative methods. In summary, this means that the following recommendations can be given:

- In early stages, one should use methods requiring a lower level of information as a data base as well as rather qualitative methods.
- In later stages, methods demanding a lower as well as a higher level of information can be used. Above all, quantitative methods of collecting statistical data can be used as well.

The classification of methods in different stages of product development is encouraged by the studies of Hales [18] or Bertsche [19]. A survey among manufacturers concerning the use of reliability methods concluded that none of them was using quantitative methods during the early stages. Rather, qualitative and quantitative experience values gained in earlier product development processes are being used. In later stages – and then always with prototypes or pre-series – the sampled companies implement concrete tests to receive a database for a quantitative approach.

4.1 Assignment of methods to the presented product models

If one tries to assign the methods for uncertainty analysis to the product model pyramid, first, the relationship between the timing of the development process and the sequence of product models can be considered. When assigning to the first three levels - which are used in the early stages - primarily qualitative methods will find use.

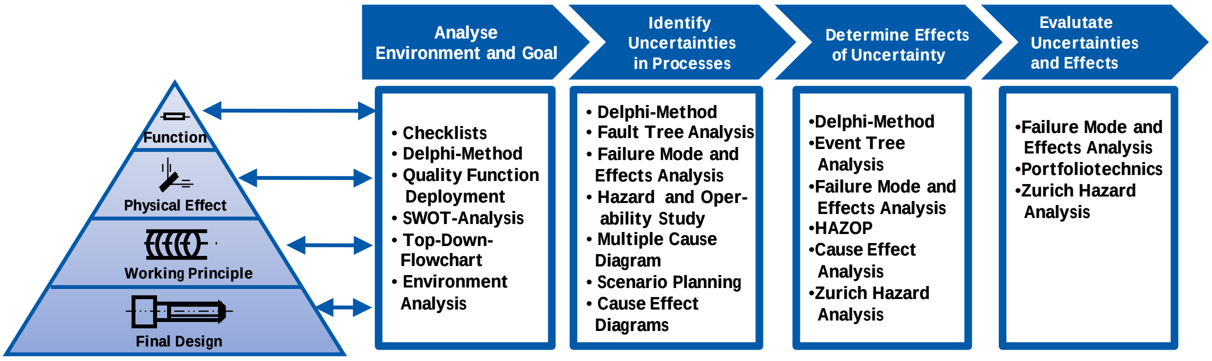

Figure 4: Linking the UMEA with the product model pyramid

As shown in Figure 4, the classification of methods bases on the previously described properties of the product models. This is also done according to the current phase of the UMEA methodology.

4.2 Methods for analysing Environment/Goal and Evaluation

To be able to determine the system, system boundaries and above all the assessment institutions, the methods of the environment and goal analysis should ideally be applied already before, but no later than with the beginning of a functional modelling. This is the only way a meaningful uncertainty analysis can take place within the function modelling. The results of the environment and goal analyses should be accessed independently from each of the regarded product models. Therefore the product models do not represent a basis for the implementation. Thus, in the selection of methods, no orientation towards the particular product model is necessary. Furthermore, during this UMEA step, a focus of analyses also lies on the product environment which usually can be considered independently from the product model level. Ideally, the environment and goal analyses should be performed only at the beginning and, in later phases, exclusively for the purpose of substantiating the results further or modifying them. Thus, this approach is similar to the inclusion of requirements which *(i)* are arranged outside of the product model pyramid and *(ii)* can be accessed from any level (according to Figure 5).

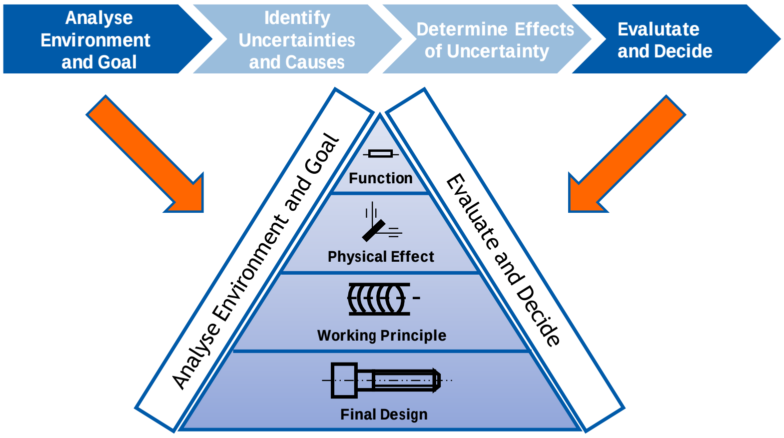

Figure 5: First step of assigning the methods to the product model pyramid

The methods for the assessment of the identified uncertainties are applicable, independently of the considered product model. This is due to the fact that they build on the previously identified uncertainties, their causes and effects. Furthermore, no direct relations to the product model exist. These methods have to be accessible from each level as well.

4.3 Methods for Identifying and Determining Effects of Uncertainty

In a further approach (see Figure 6) the methods of UMEA steps for identifying uncertainties, causes and effects should be investigated on their assignment. At the functional level, both the fault tree analysis (FTA) and the event tree analysis (ETA) can be used to identify causes and effects of uncertainty. Both methods assume an undesirable event, for example in the form of a malfunction. Thus, by negation of certain product features, both the causes and the effects of such a failure can be determined. The specific form of representation at this level would help these two methods as well. Both can work with logic operations. The system FMEA can be used at the functional level, since the FMEA examines *(i)* the interaction of individual system elements and malfunctions as well as *(ii)* causes and consequences of error on the high level of abstraction. On the level of working principle, prime concept designs will be judged by the use of a FMEA system. Due to its comprehensive nature, the Zurich Hazard Analysis (ZHA) can examine all aspects of a system: *(i)* the functions and hazardous properties of substances, *(ii)* external factors and *(iii)* operator errors [20]. Thus, besides using the method at the functional level, it may also be considered at other levels. Ponn/Lindemann suggests the use of creativity techniques to be able to detect negatively affecting functions of a technical system with the help of a functional model [21]. The advantage of an uncertainty analysis at this level is the representation of a product without a prefixed solution. Uncertainties can be identified which occur independently of a possible solution and which are based on the functions of the technical system. Above all, at effect model and working principle level (which in practice may not always be separated), the Hazard and Operability Study Method (HAZOP) can be used, since this method *(i)* disassembles the system and *(ii)* considers various system states and system parameters (pressure, flow, voltage, etc.) [16].

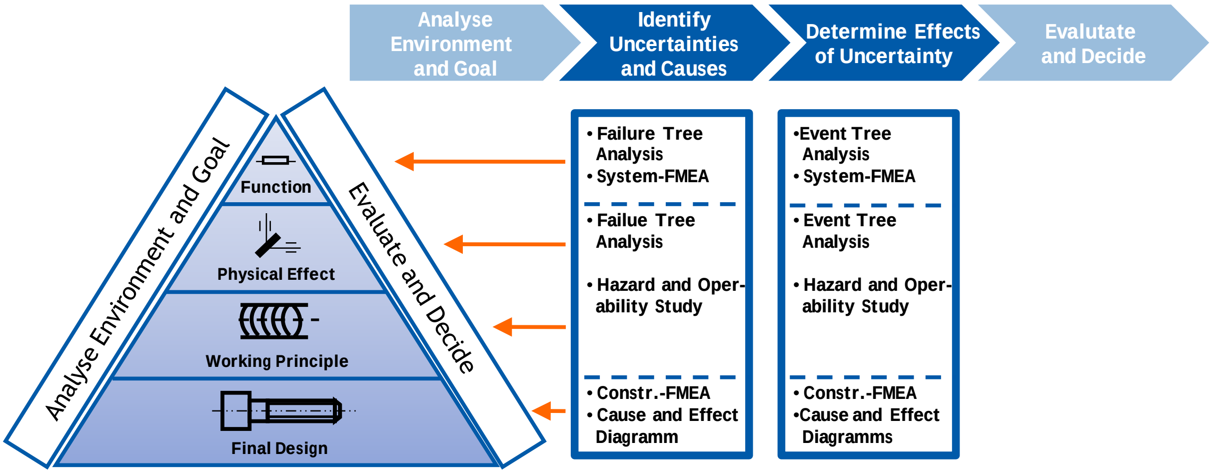

Figure 6: Second step of assigning methods to the product model pyramid

The consideration of product and process properties is only possible if the functions are assigned to physical effects or mechanisms of action. Of course, both the ETA and the FTA are used in these two levels, since only one adverse event is required as a trigger. The complexity of this tree will increase in any subsequent phases. So, these two methods are especially well suited for use on an abstract level. [22]. At final design level, the Design FMEA can be used. It examines the design and layout of product elements and is mainly used at the component level. Besides the previously mentioned HAZOP method, at this level of the product model pyramid also the cause-effect diagram (Ishikawa diagram) can be used. An application on the more abstract levels is not recommended, since, just when the recommended 5 M's (machinery, manpower, material, measurement and method) are used to identify the causes, a very practical basis is required. Due to their exploratory character, the Delphi analysis and the scenario planning can be used at all levels. The same is true for the cause-effect matrix which seeks to determine possible connections between causes and effects. In contrast to the previously discussed methods, these methods have no properties that stand for a special use in a certain level.

5 EXAMPLE FOR LINKING THE METHODS

By way of example, the presented and selected methods will be linked to a chain of effects along the UMEA phases (shown in Figure 7). Here, the methods are not always used as a whole.

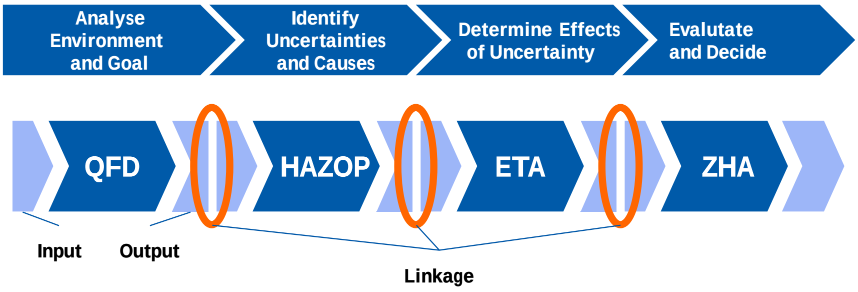

Figure 7: Linkage of qualitative methods within the UMEA

In some cases, a modular approach of the methods is made. So only those elements are applied which are useful in the combination of the particular UMEA step and the upstream respectively downstream methods.

Starting from a QFD in the first UMEA step, the environment "Customer" will be integrated into the uncertainty analysis (Figure 8) for the example of a turned shaft. The QFD via the HOQ (House of Quality) provides the basis for subsequent UMEA phases. With the help of the HOQ the customer's relevant product features and components can be identified. So in the following steps, components and functions can be subjected to uncertainty analysis which show the high technical demands and simultaneously have high customer relevance. Furthermore, the importance of technical requirements from the customers view (determined by the HOQ) may directly feed into the assessment step of the UMEA, if those requirements cannot be met due to uncertainties. Hence the HOQ offers an ideal introduction to an uncertainty analysis, as the detected features and components can be examined for uncertainties in the next step by using the HAZOP process. Thus, the HAZOP procedure is used for identifying uncertainties in the second step of the UMEA.

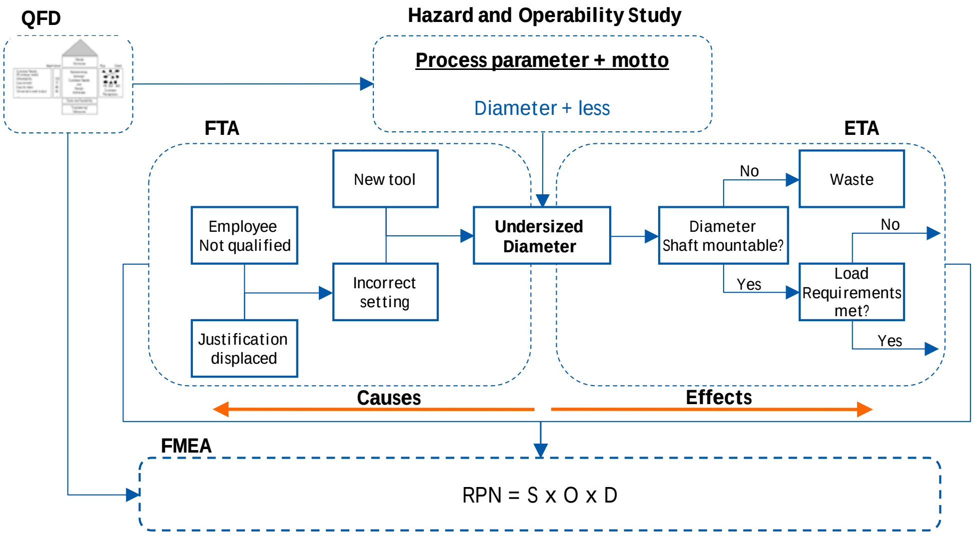

Figure 8: Exemplary implementation of method linking

With the HAZOP process uncertainties can be determined in form of their probability of occurrence. The impact of deviations from nominal variables in product and process properties, presented after the second HAZOP step, can be examined through the FTA and ETA. The ETA is applied in the third step of the UMEA while identifying uncertainty effects. FTA and ETA can be carried out simultaneously, since both regard an adverse event as their output (thus an uncertainty identified with the help of the HAZOP process).This simultaneous approach has great temporal benefits. In addition to possible causes of uncertainty, the FTA provides the probabilities of occurrence of the uncertainties, which are needed to assess the uncertainties in the fourth UMEA step. In the fourth step of the UMEA, uncertainties identified and analysed of HAZOP, FTA and ETA are assessed.

The assessment is independent of the previous steps and can, for instance, be made by risk, reliability or cost. For the early stages of product development, the linkage is illustrated in case of risk assessment. For this purpose the risk assessment within the FMEA can be used. The risk priority number (RPN) used by the FMEA to evaluate the risks considered, is composed of the factors probability of severity (S) the uncertainty, the occurrence (O) and the probability to detect (D) the uncertainty.

Concretely the used methods can find intersections to the FMEA factors. As the importance of the component etc. tested for uncertainties was determined from a customer perspective, the results of the HOQ can be included in the severity (S) for the customer. The results of HAZOP and FTA can be used to determine the probability of occurrence (O). The results of the ETA can enter the probability of detection (D) as the ETA determines uncertainty effects which can be used to estimate to what extent uncertainties can be found. The methods chain derived in the UMEA can be illustrated by a production process. Detached from the presented manufacturing process, only the sub-process “thread turning” is considered for this purpose. In the first step of the UMEA and with the help of the HOQ, the shaft diameter was determined as an important “cause” property for (consequent) properties for the customer. Using the HAZOP procedure with the guideword "less", the uncertainty "undersized diameter" was identified. With the help of the FTA and the ETA, this deviation from the expected value is then analysed on possible causes and effects. As a possible cause, an incorrect setting of the lathe can be identified. Regarding the possible effects, it is crucial for instance whether *(i)* the shaft with the undersized diameter can still be mounted or if *(ii)* it can meet the given load requirements. An assessment of the possible uncertainties and their impact can be made by the FMEA. This allows *(i)* building a hierarchy of levels of impact as well as a hierarchy of probabilities of occurrence of uncertainty and furthermore *(ii)* to identify those.

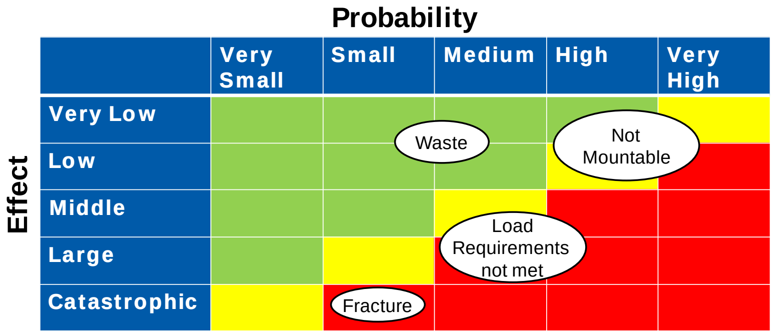

Figure 9: Event of an undersized diameter assessed with a ZHA matrix

For analysing and displaying the evaluation results, the Zurich Hazard Analysis (ZHA) is used. Here, the probabilities of occurrence and the impact of analysed uncertainties are recorded in a matrix (Figure 9) from which acceptable and unacceptable uncertainties can be derived. Even in this purely qualitative approach to the evaluation of uncertainty, links with the previous methods exist. As before, the regarded variables can be derived from the FTA and the ETA. The results of the HOQ could eventually be involved in the effects.

6. DISUSSION AND FUTURE WORK

As a result of the chosen combination of methods, a partial parallelization of UMEA step two and three will be achieved by the methods of FTA and ETA. This simultaneous approach can lead to time savings in the implementation of UMEA. A further advantage of linking methods is that the FTA can be used both qualitatively and quantitatively. This results in the possibility to adhere to this method as long as the UMEA is performed fully quantitatively. Since, when considering a different assessment institution (e.g. environmental impact), the only requirement is passing forward the system parameters to be examined from the first UMEA step to the following HAZOP method, the variable link to a method for environment and target analysis supports this methods linking as well. After that, the remaining method chain in the UMEA can be used independently of the method used in the first UMEAstep and remains in their linkage.

A disadvantage might be seen in the partially quite complex implementation of the FTA and the ETA. Consequently, before using the method, considerations should be given whether *(i)* a detailed approach is necessary or *(ii)* a methodical approach with a lesser extent leads to similar results. To be able to implement complex evaluations, as future work, it is necessary to find strategies to reduce the number of uncertainties to be evaluated [23]. So far the focus was on the qualitative methods of uncertainty analysis. To this day, the use of quantitative methods within the UMEA and their linkage is a research field, which has to be considered in the context of the development of the UMEA [24]. Furthermore, it should closely be looked at the problem of data quality. In the example, only qualitative differences in form of estimated uncertainties were considered. In regard to the use of quantitative methods, it must be verified whether it can be applied to *(i)* a sharp mathematical linkage of data and *(ii)* process uncertainty.

7. CONCLUSION

Different methods could be assigned to different levels of the product model pyramid. However, only a concrete assignment of methods identifying uncertainties, their causes and effects makes sense. This paper shows that the environment and goal analyses as well as the uncertainty assessment should be implemented independently of the particular product model. Furthermore, methods exist that are specially suitable for early stages, for example FTA, ETA and system FMEA at a functional level. Besides, there are methods, such as the Delphi method that can be applied independently from any model at all levels. The link between the UMEA and the product model pyramid used in the product development has shown, that the UMEA steps of the environment and goal analysis as well as the judging and decision making are located outside of the product model levels. Just in the steps of identifying uncertainties, their causes and effects, a distinction between the particular product model levels must take place. In early stages rather qualitative methods should be used, as well as methods for obtaining information and methods that can deal with little available data/information. Generally in later stages, a greater use of methods is possible. Specially, it is possible to use quantitative methods and methods, establishing on a wider range of information base (due to the higher probability that statistical data are available). Many of the methods considered in this study have a high level of complexity (e.g. QFD and FTA) and hence have high demands on their implementation (for example, on the capabilities of the user but also on temporal resources). The acceptance of such methods is not always given as well. Consequently, it must be the aim of further research to make the UMEA comprehensive and powerful. But at the same time, the needs of the users have to be considered, since only then the acceptance can be created which is required for the practical implementation.

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REFERENCES

[1] Hanselka, H. and Platz, R., Ansätze und Maßnahmen zur Beherrschung von Unsicherheit in lasttragenden Systemen des Maschinenbaus – Controlling Uncertainties in Load Carrying Systems“, published in *Konstruktion*, VDI, November/December 2010, pp53-64

[2] Engelhardt, R., Birkhofer, H., Kloberdanz, H, Mathias, J., Uncertainty-Mode- and Effects-Analysis. An Approach to Analyse and Estimate Uncertainty in the Product Life Cycle, in: *International Conference on Engineering Design, ICED´09 Vol 2*, Stanford, 2009, pp191-202

[3] Browning, T. R., Eppinger, S. D., Modelling Impacts of Process Architecture on Cost and Schedule Risk in Product Development. *IEEE Transactions on Engineering Management*, Vol. 49(4), 428-442

[4] Grebici, K., Wynn, D., Clarkson, P. J., Describing Information use in Engineering Design Processes Using a Diagrammic Model, in: International Conference on Engineering Design, ICED´09, *Vol. 1*, Stanford, August 2009, pp. 571-582.

[5] Morgan, M. G., Henrion, M. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, Cambridge University Press, Cambridge, UK, 1992

[6] Knight F. H., Risk, Uncertainty and Profit. Augustus M. Kelley, New York, 1964

[7] Thunnissen, D.,P., *Propagating and Mitigating Uncertainty in the Design of Complex Multidisciplinary Systems*, 2005, PhD thesis California Institute of Technology, Pasadena,

California, California Institute of Technology.

[8] Radner, R., Competitive Equilibrium Under Uncertainty, in: Econometrica, 1968, Vol. 36.

[9] Chalupnik, M.J., Wynn, D.C., Clarkson, P.J. (2009): Approaches to mitigate the impact of uncertainty in development processes, in: International Conference on Engineering Design, ICED´09, *Vol 1*, Stanford, August 2009, pp. 459-470.

[10] de Weck, O. and Eckert, C. A classification of uncertainty for early product and system design, *in: International Conference on Engineering Design, ICED'07*, Paris, France, 2007.

[11] Knetsch, T., *Unsicherheiten in Ingenieurberechnungen*. PhD thesis, Shaker, Magdeburg, 2004.

[12] Zimmermann H. J. *An Application-Oriented View of Modeling Uncertainty*. European Journal of Operational Research 122, pp.190-198, 2000.

[13] Grebici, K., Wynn, D. C., Clarkson, P.,J.: Modelling the Relationship between Uncertainty in Design Descriptions and Design Process Duration, *in: Proceedings of IDMME – Virtual Concept 2008*, Beijing, China, 2008.

[14] Engelhardt, R., Enss, G., Koenen, J., Sichau, A., Platz, R., Kloberdanz, H., Birkhofer, H.,Hanselka, H., A Model to Categorise Uncertainty in Load-carrying Systems, *in: Proceedings of the 1st International Conference on Modelling and Management Engineering Processes*, 19.-20.Juli 2010, Cambridge/UK, pp. 53-64.

[15] Andreasen, M. M., Hein, L., *Integrated Product Development*, Bedford, Berlin: IFS (Publications) Ltd, Springer, 1987.

[16] Sauer, T.: *Ein Konzept zur Nutzung von Lösungsobjekten für die Produktentwicklung in Lern- und Anwendungssystemen*, PhD Thesis, VDI Verlag, Düsseldorf, 2006.

[17] Verworn, B (2007): Die frühen Phasen der Produktentwicklung am Beispiel des Maschinenbaus und der Elektrotechnik, *in: Herstatt, C./Verworn, B., Management der frühen Innovationsphasen. Grundlagen – Methoden – Neue Ansätze*, Vol 2, Wiesbaden 2007, pp. 357 – 381.

[18] Hales, C. *Analysis of the Engineering Design Process in Industrial Context*, Ph.D. thesis, University of Cambridge, 1987.

[19] Bertsche, B., Göhner, P., Jensen, U., Schinköthe, W., Wunderlich, H.-J., *Zuverlässigkeit mechatronischer Systeme*, Springer Berlin, 2009

[20] Adrian V. Gheorghe and Ralf Mock, *Risk Engineering: Bridge Risk Analysis with Stakeholders Values*, Kluwer Academic Publisher, Dordrecht, 1999.

[21] Ponn, J., Lindemann, U., *Konzeptentwicklung und Gestaltung technischer Produkte. Optimierte Produkte – systematisch von Anforderungen zu Konzepten*. Springer, Berlin, 2008.

[22] Suzuki, K., Kameyama, Y., *Application of Knowledge Automated Fault Tree Synthesis Based on Decision Table*, Safety Engineering 28, pp. 291-303

[23] Pahl, G./Beitz, W./Feldhusen, J./Grote, K.-H. (2007): Pahl/Beitz – Konstruktionslehre. Grundlagen. 7. Aufl., Springer, Berlin 2007

[24] Browning, T.R., J.J. Deyst, S.D. Eppinger and D.E. Whitney (2002) "Adding Value in Product Development by Creating Information and Reducing Risk," *IEEE Transactions on Engineering Management*, 49(4): 443-458.

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