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AN APPROACH OF A MODEL TO DESCRIBE UNCERTAINTY IN TECHNICAL SYSTEMS

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1. Introduction

While developing technical systems at the engineering process uncertainties always appear if there is a lack of information about the actual performance records of product and process properties which have to be anticipated during the development process. Uncertainty occurs in all phases and thus decisively influences process properties and thereby product properties. According to the definition of uncertainties in technical systems uncertainties exist as far as product and process properties are not determined and deviations of these properties arise [Engelhardt, 2009]. Based on this definition of uncertainties a complete model of uncertainties is being developed in this paper, where uncertainties can be identified on different levels of abstraction. These uncertainties have to be taken into consideration during the planning and developing processes. This is especially necessary while building the model, forecasting the technical product and process properties and while determining the surrounding conditions. The system of uncertainty models has to allow classifications under real life cycle processes. Such as changes because of occurring stress or procedures which differ from the forecasted properties. This classification of uncertainty models to analyse uncertainty has been exercised exemplarily by Pahl and Beitz [Pahl, 2007] by means of the product development processes. It enables the assignment of suitable models of uncertainty at different levels of abstraction with the aim to ensure the classification of uncertainty. Based on this model it is a decisive part of these models to derive suitable methods which help reducing the lack of knowledge. Within the field of engineering material and stress uncertainties are used e.g. for machine elements in particular, including the mathematical detection of statistical distributions. In addition to qualitative calculation methods, differentiated and sophisticated methods of probability calculation are used as well. Especially within the product development process, subdividing uncertainty in a model of uncertainties is essential for deriving matching methods which can reduce the lack of information.

2. Review on relevant uncertainties

During the early stages of the product development process decisions that will have a variously strong impact on the future product have to be made. At this point uncertainties appear among processes and they will spread through successive processes. In the early stages of the product development the knowledge of a future product is still low. And there is a high level of uncertainty regarding both, the processes to be expected as well as the properties of a product [Lindemann, 2008].
For real products and production processes there are uncertainties either in terms of unsteady output values (regarding product properties) or in terms of diverging uses of the products. The analyses and classification of uncertainties is mainly used within the field of 'business studies'. Here the 'decision theory' is applicable. By adding information uncertainty can change its status.

The conceivable surrounding conditions play a major role when describing varied courses of action. This is due to the fact that decisions made under the assumption of one certain environmental state might not match with such made under a different assumption of the environmental state [Laux, 2005].
The range of different classifications illustrates the variety of uncertainties that can be summed up in models. The classification has taken place in different scientific disciplines. Various elements of uncertainty are being integrated. For the formulation of a sustainable model of uncertainty (usable at any state of development), it is essential to build 'model systematics' first. The reason for this is that the 'model systematics' themselves are based on well-defined 'standard models' which reflect uncertainties.
According to Pahl and Beitz [Pahl, 2007] the product development process can be adopted while classifying uncertainties (at the level of models). VDI guideline 2221 proposes a general, industry-independent procedure model for the development of technical products.
The procedure contains seven individual operations. Each operation can be associated with an output.
Multiple steps of procedure can be summarized to phases.

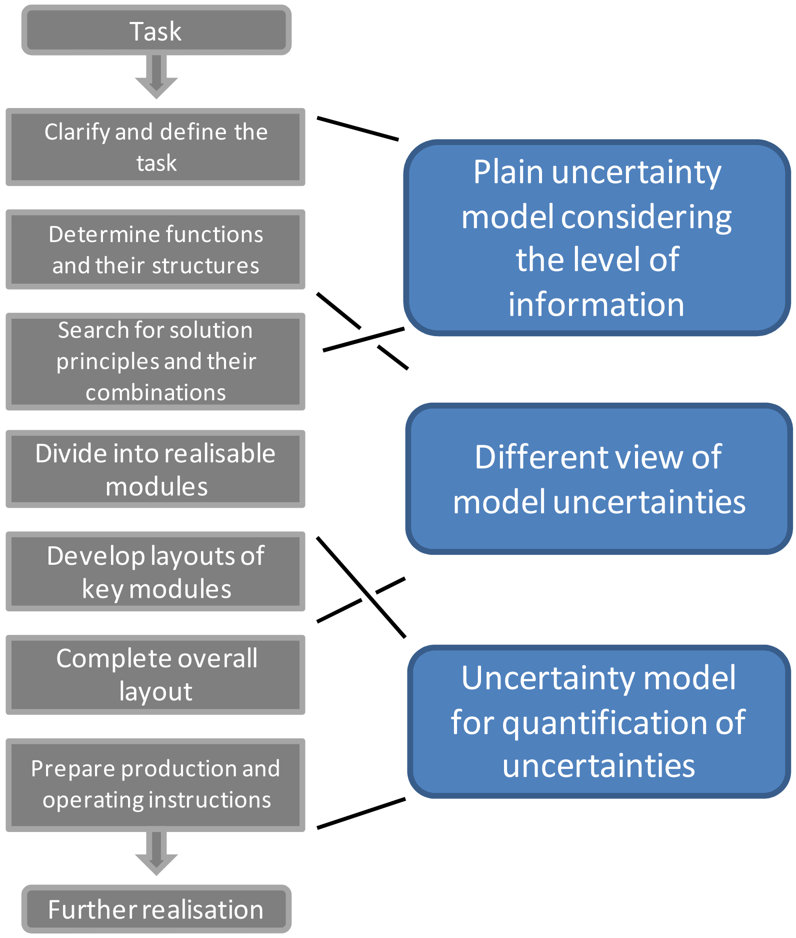

Figure 1. Uncertainty models according to VDI 2221 guideline

Regarding the procedure of VDI guideline 2221, you can notice that all activities during the product development process are structured and refer to defined outputs.
Concerning the steps of procedure, the focus of consideration lies on the process that is divided into individual operations.
The relations between the individual working process outputs are not shown. Nevertheless, the steps of procedure illustrate that the successive development of technical systems (from abstract to concrete) takes place in the sequence of individual working processes [Sauer, 2006].
The modular structure of the working process output ranges from the phase 'create list of requirements' to the phase 'write product literature of the end product'. Thereby uncertainties that have

not been described so far can emerge in any phase. Those uncertainties can be extended by different models to structure various uncertainties in general. The purpose of the structure is to enable an assignment of all kinds of uncertainties to classify them this way.
By means of dividing and using different models of uncertainty it is easier to predict and structure uncertainties. In different stages of the product developing process different kinds of uncertainties can be re-used. This data can also be employed to choose matching methods.
The various working process outputs (during the successive development of technical systems from the abstract to the concrete) mainly correspond to the sequence of these individual operations.

3. Classification of uncertainties

There are different models of uncertainty or representations by means of which you can classify miscellaneous forms of uncertainty. It is possible to deflect different statuses of uncertainty out of the different models of uncertainty. The classification results from a bottom of uncertainties which occurred out of coincidental parameters. This classification was also carried out in the sector of nuclear energy which accepts a failure concerning a natural, statistical fluctuation. This natural fluctuation can appear in the environment as well and cannot be further reduced. Another approach to a holistic view (which is however limited to safety aspects) comes from a model-based analysis with system models.

3.1 Aleatoric and epistemic uncertainty

While interpreting and calculating e.g. procedural devices it is differentiated between aleatoric and epistemic uncertainties and their reproduction is considered (see Figure 2) [Knetsch 2004].

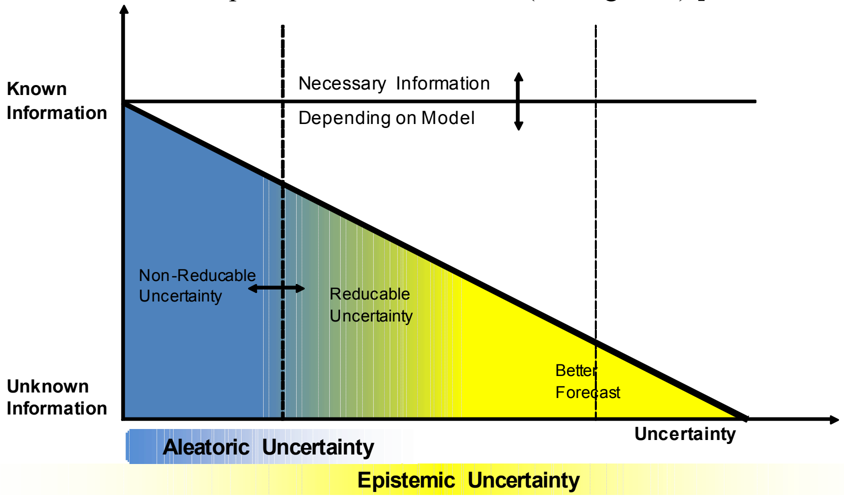

Figure 2. Properties of Uncertainty and Information

Aleatoric uncertainties contain the coincidental variation of sizes which normally cannot be further reduced. The aleatoric uncertainties appear predominantly in the real product life cycle at a steady state process.
Generally aleatoric uncertainties are quantifiable, expressible through stochastic terms and calculable by means of probalistic methods [Aughenbaugh, 2006].
You can imagine a turning process in which an axle is turned off on a certain diameter for example.
Aleatoric uncertainties would be a fluctuation in process temperature from summer to winter which affects the turning process. All these casual parameters in the life cycle process can cause fluctuations in properties through production and in the behaviour of the products through use. Prerequisite for the reduction of the impact of aleatoric uncertainties is that they are generally identified and, only then, the range of fluctuation of product and process arrangement can be considered.
Epistemic uncertainties are caused by insufficient information about the product or the process. Due to lack of knowledge reality is only reflected incompletely, deficiently and not explicitly enough. This kind of uncertainties increasingly appear in the virtual product development process because

information and knowledge are gained only. This type of uncertainty is described best with the help of intervals [Aughenbaugh, 2006]. Different models, their parameters, the data collection and process technologies can make a contribution to epistemic uncertainties.
At early levels of concretion a concrete declaration of an axle diameter with complete information concerning the allocation of tolerance is still very improbable. Nevertheless, boundaries can already be defined in which the diameter can be estimated. Furthermore, the choice of a proper method of production could only be possible and reasonable at the same time from a certain level of concretion on. The estimation of available information, methods for information acquisition and also the inserting of experience could help to recognize and reduce epistemic uncertainties.
The differentiation between the terms aleatoric and epistemic uncertainty is shaped through the terms 'risk' and 'uncertainty' in the area of business administration. [Chalupnik, 2009]

3.2 Lack of knowledge and definition

Kreye et al [Kreye, 2009] tries to classify the causes for uncertainties by dividing uncertainties in lack of knowledge and lack of definitions (see figure 3).

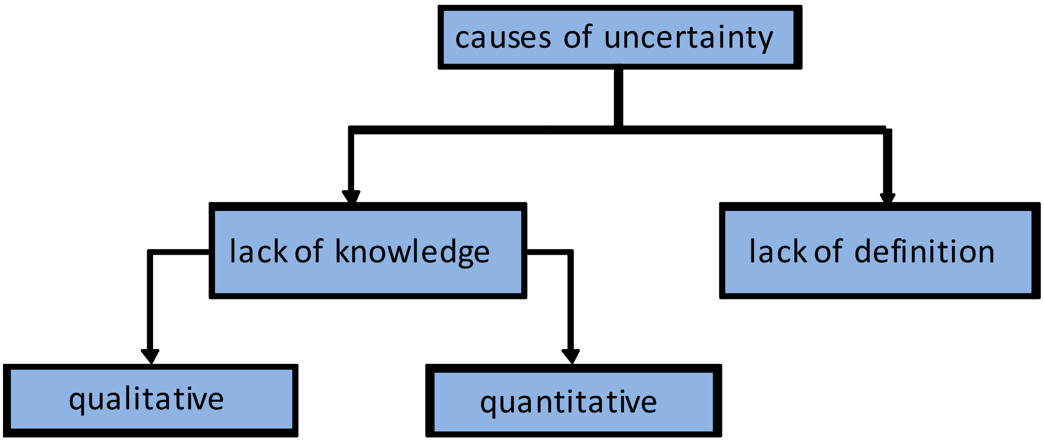

Figure 3. Causes of uncertainty

The lack of knowledge and the lack of information are respectively mentioned as the main reason for uncertainty to arise. This occurs when important information which is needed in the current moment is not available. The lack of knowledge can be subdivided in qualitative and quantitative uncertainty. An example for a qualitative lack of knowledge are information which are available but situations can not be described deterministically with (for example physical variables which cannot be measured). A quantitative lack of knowledge exists if any information about other statuses of decisions are missing [Conway, 2007].
The second area is composed out of a lack of definition. Here the term 'imprecision' is often used. That means that information about a system is not decided or specified yet. This is e.g. a specification sheet or a contract specification.

An other Model of Uncertainty

The introduced models provide general and specific classifications as well as definitions of uncertainty. The classifications from various fields lead to an additional classification for the design of complex systems: ambiguity, epistemic uncertainty, aleatory uncertainty and interaction (Thunnissen, 2005). The classification underlines that uncertainty is a condition of not knowing. It formally defines uncertainty as the difference between an anticipated or predicted value and an actual value in future. For technical systems some parts of the model can be well adopted. However, effects of uncertainties are missing. Concluding, none of the previous classifications are adequately applicable to the classification of uncertainties in technical load-carrying systems, because this requires a procedure model taking effects of uncertainty into account. The newly developed model of uncertainty is based on the preceding models.

4. Uncertainty models for technical systems

4.1 Model for early development phases

Especially for the sector of technical systems it has been shown that a simple classification of uncertainties is not constructive. At different levels of abstraction of development processes and different detailedness of a life cycle process of production and process of usage a different occurrence and evaluation of uncertainties is necessary.
With the help of differentiated models of uncertainty it is reasonable to make a classification of different models of uncertainty to examine the different granularity of the available information.

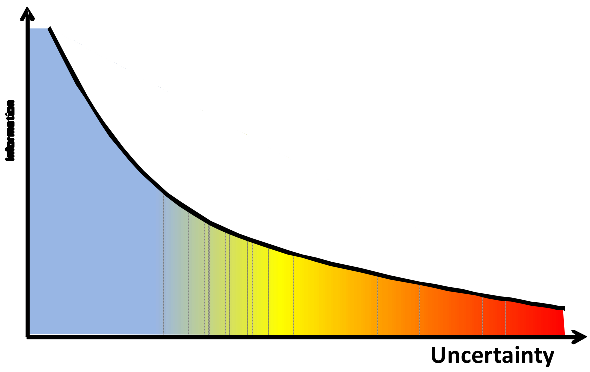

Figure 4. Uncertainty and information

Especially the first connection is relevant for the early phases of the development process in which information and uncertainty are brought in connection. This connection is not linear because it does not reflect reality in general. In particular, the curve should not intersect the axes because it can neither be considered that no information is available (absolute ignorance) nor that other uncertainties may be completely excluded by providing information.
The first connection, which is relevant especially for the early phases of development process, would be the information in connection with uncertainty. This classification makes it possible to realise a rough classification of uncertainties.
In Kreye´s [Kreye, 2009] classification this would be the case if there is a lack of definition. The system is not described properly, decisions are not made yet. You are approximately in the area of requirement finding when it is still working without models. It is possible to give a rough appraisal as well as dimensioning or estimation of costs in early phases. The knowledge, which predominates during a new development can be covered through the classification of uncertainties.

4.2 Model for effect chains and physical effects

Knetsch [Knetsch, 2004] classifies uncertainties concerning the prospective condition of the system in aleatoric and epistemic. By today’s point of view, this classification must be further differentiated and regarded independently. Prognosis uncertainties exist if product and process characteristics for the future have to be measured. You can find prognosis uncertainties by regarding the life cycle. They appear in case the customer needs changes during the development process or during the expected useful life. It may happen that products and processes cannot be adapted to the enhanced technologies or a changed competitive situation. If the product has to be created for future production and use cycles prognosis of uncertainties dominates.
A further step into the subdivision of uncertainty would be the classification in aleatorc, epistemic and prognosis uncertainty [Engelhardt, 2009]. There the concept is the main centre of attention. It would be the creation of product models with sufficient level of detail. A classification of uncertainties according to functional and active principals also makes sense. Its advantage is the division into different classes of uncertainty (see Figure 4).

Information is an important input, especially in early phases of the development process. Information describes a condition in which different classification of information can be described. The information about uncertainties can be classified in quantitative and qualitative systems.
The previous classification of uncertainties shows aleatoric, epistemic and prognosis uncertainties which have their own structure for the regulation at effect level as well as effect structure level.

Figure 5. Allocation of aleatoric, epistemic and prognosis uncertainties

In case of aleatoric uncertainties all randomly occurring product and process properties are collected. These can also be variations that arise during the development process. These fluctuations of product properties can occur coincidentally. It makes sense that these are included during the development process particularly impacts on the product.
Epistemic uncertainties are registered uncertainties during the development by using models. This especially includes abstract, provisional and incomplete product models.
The use of prognoses by means of systematic anticipation of 'all' product and process properties during the whole development process can support them. These uncertainty models of prognosis are suited to the forecast of future properties in the development process. This can be realised through special methods of prognosis which make it possible to predict future properties.

4.3 Model for quantification of product and process properties

The model has to ensure that uncertainties of product and process properties are classified more precisely. Also a differentiation between qualitative and quantitative uncertainties has to be classified as well. Therefore, a model of uncertainty from the sector of business administration for technical systems was modified by the Collaborative Research Centre 805. It should not be gone into explicitly at this point here. With this model of uncertainty a classification can be made which allows a differentiation between qualitative and quantitative uncertainties.
In this model of uncertainties processes and properties in the sector of components can be classified. For an examined process a categorization is made for any property. Depending on the classification in the decision tree the examined uncertainty is classified in three different categories. This classification is done in ignorance, uncertainty and stochastic uncertainty. It is yet important to mention that rather than sharp boundaries, smooth transitions exist between the three categories. The procedure of assigning a considered uncertainty to one of the mentioned categories via the depicted decision tree will be examined in the following section. Here, speaking of an uncertain property means that the process of determining the property is uncertain.

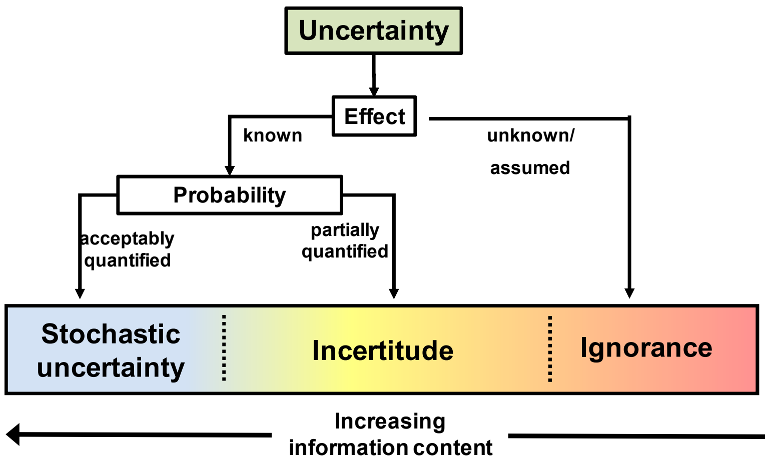

Figure 6. Model for qualitative and quantitative uncertainties

Ignorance describes the situation that neither the effect nor the resulted fluctuation of a disturbance variable of an uncertainty parameter are known. Because of that decisions cannot be considered. Incertitude (in sense of not knowing the exact density function) describes the situation that for the uncertainty parameter, effects and resulting fluctuation of a disturbance variable are principally known but without any allocative function.
Stochastic uncertainty is given when the fluctuation of the final process condition (uncertainty parameter) – which is a result of a failure – is completely described by a allocative function.

4.4 Holistic model of uncertainty based on the development process

By connecting the different models of uncertainty to a holistic base model you get a holistic model of uncertainty. This model of uncertainty is used as a model system to analyse uncertainties above all and to choose or develop methods for them. This shaping of uncertainties is the first step for a complete uncertainty analysis methodology by which it will be possible to classify and analyse uncertainties on a different level of abstraction. By this the model of uncertainty already allows to evaluate uncertainties qualitatively in early phases of development by presenting a classification with a grade of information already available.
To be able to locate uncertainties at different levels of ascertainment, it is important to have a multiplicity of possible product models to fall back on. On the basis of functional structures it is already possible to identify uncertainties roughly at this stage.
Normally uncertainty in a technical system goes up the bigger the number of functions between input and output is. A higher rate of uncertainty during development, production and use is to be expected particularly when energy converting processes are executed.
For the physical effects it has to be analysed, whether in general, there is a lower uncertainty resulting from the combination of certain effects.

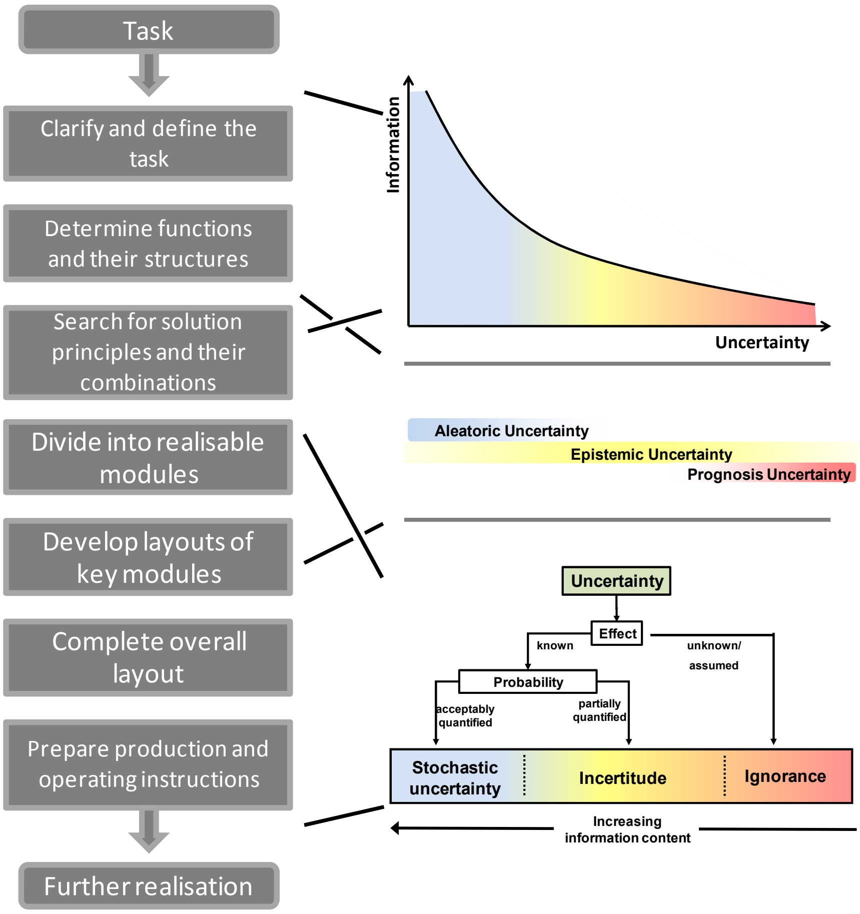

Figure 7. Uncertainty model for the development process

Regarding product models uncertainties predominantly arise while combining different effects. Because of the high level of abstraction a differentiated linkage of the effects with the corresponding uncertainties will be difficult. The active structure differs from that. With this kind of product model effect pairings can be described abstractly. At this point, it is easy to combine the effect pairings with uncertainties. Depending on the acting force and relative velocity uncertainty can be determined more precisely. At the level of the device's architecture uncertainties can be located with an even higher precision. Particularly dimensional accuracy can be determined and thus uncertainties can be referred to. The reflection of uncertainties within product models (of the product development) predominantly refers to uncertainties in product properties. Normally uncertainties in the behaviour of products are not illustrated in these product models. The correlation of product models and uncertainties is getting reduced to two insights: first, the reflection of uncertainties can take place in different levels of abstraction and second, the product always needs to be seen in context with a process.

5. Exemplary application of the classification of uncertainty

An example is given to illustrate the classification of the various models even more clearly. The technical system to be analyzed is a hydraulic cylinder, in particular its piston rod. Especially in the early phases of the product development, the requirements determination is in the foreground. To be able to estimate uncertainties in these phases, a classification according to their level of information is performed. The latter is chosen since it aids to provide a rough classification of uncertainties. For the subsequent developing process of this example, many different properties concerning the fulfilment of the tolerance requirements have to be considered. Besides the important properties ´total length´ and ´diameter´, properties as cylindricity, radial run-out, roundness, concentricity, straightness, surface hardness and hardness depth of the piston rod are in the focus. To some extent, those properties appear at several points of the cylinder piston rod. As a result they have to be considered separately at each of these points. Particularly in the fields of functions, physical effects and active principles the classification into aleatoric, epistemic and forecast uncertainties can be useful.

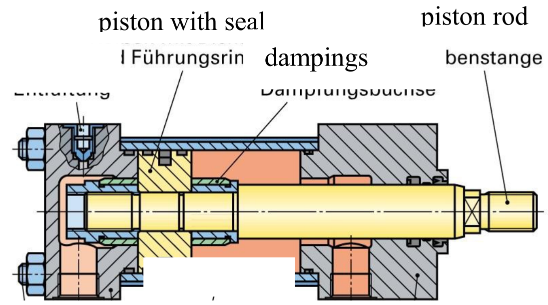

Figure 8. Example of an hydraulic zylinder

Progressing the development process in the range of detailed elaboration, the second field (with diameter and cylindricity, concentricity, radial run-out and roundness) will be considered within this process chain example.
This field demands exact knowledge of the currently existing level of information since as of now CAD sketches can illustrate uncertainties as probability mass functions. The classification into stochastic uncertainty, incertitude and ignorance is performed by means of the model of uncertainty.As listed below, four principles have been revealed for the model of uncertainty. Subsequently each will be discussed. Within the model of uncertainty, individual properties or property vectors of products/processes can be considered at a certain time. Uncertainties within the presented model of uncertainty do not necessarily involve a distribution function of a property. But rather multiple properties can be described by giving a multidimensional distribution function. The matter is a snapshot at the current level of information, thus at a concrete time. A consideration of the uncertainty progression over time cannot be illustrated by this model. Therefore a third level would be necessary since the growth of information does not develop analogously to the passage of time. However, a temporal development of uncertainties can be considered by taking several snapshots. For

this purpose concepts from the probability theory exist where stochastic processes are being regarded as increments of time. Transition probabilities from on condition to the temporally closest following condition can be described by these concepts.
No model uncertainties are illustrated by the presented model. Uncertainties about product and process properties are described instead. Eventual simplifications as for instance a mechanical analogue model are no uncertainties within our scope since they consciously mirror realty incorrectly. Neglecting the damping when modelling a dynamic system for example represents no uncertainty. However, variations in the damping of a real system are uncertainties.
Here, a categorisation of uncertainties occurs at the current time and according to the individual state of knowledge. The individual state of knowledge resp. level of information is decisive when categorising uncertainties. A specialist within a specific field for instance disposes of a broader knowledge about this field than an amateur. Thus due to the acquired expertise, one could categorize a property as an incertitude whereas an amateur might categorize it as ignorance. For process properties rather than for product properties the differentiation according to effects plays an important role within the uncertainty categorization.

5. Conclusion and Outlook

Different kinds of methods can be attributed to the model of uncertainty. This allocation is made by a classification of qualitative and quantitative methods. Qualitative methods are proper in the beginning phase of the product development in which a disambiguation is necessary and the processes and properties are not available in detail. These uncertainties arise when there is ignorance and lack of information.

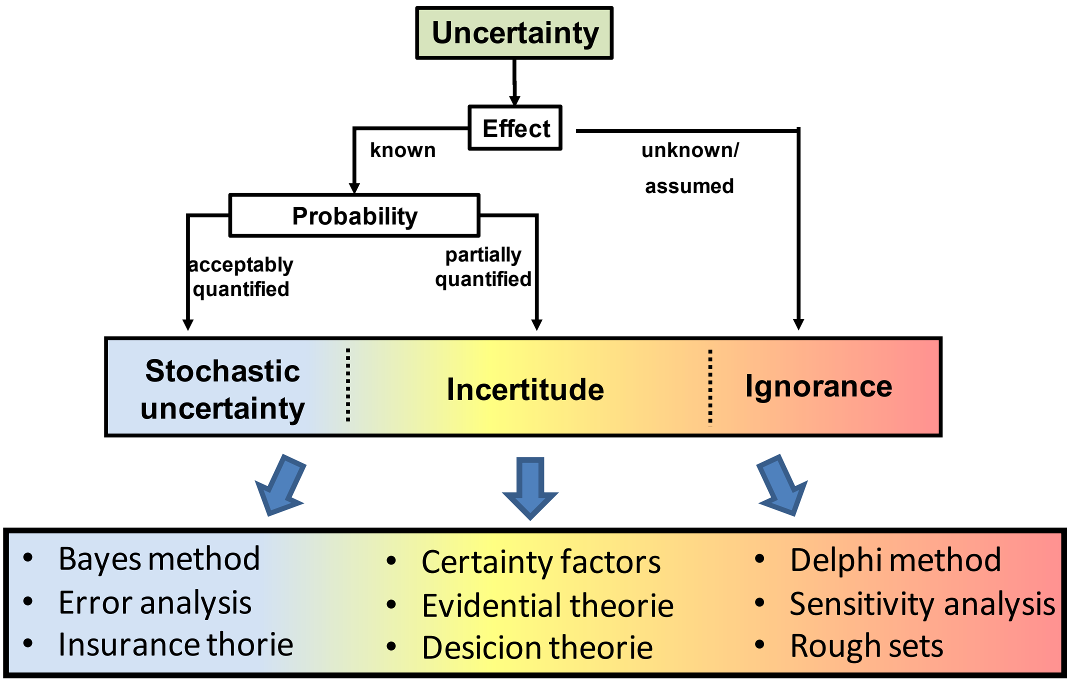

Figure 9. Uncertainty model for the development process

The qualitative examination of uncertainties in a system is advantageous because it is executed faster when you have less information and it develops the appreciation of the system. To reach a more precise analysis, which, amongst others, declares the potential of system optimization or the process chain, it is generally easier to do it on the basis of a quantitative model. This kind of model also tries to image a formalistic relation of uncertainties in which attributes of a model interact.
The allocation of relevant methods will be a perspective of the further usage of the model of uncertainty.

Acknowledgement

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