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Manifestation of uncertainty - a classification

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MANIFESTATION OF UNCERTAINTY - A CLASSIFICATION

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ABSTRACT

The aim of the research presented in this paper is to propose a classification of the manifestation of uncertainty to offer a basis for a shared understanding and characterization of the concept of uncertainty within the area of design research. During the past decade a growing number of papers about uncertainty have been published. These papers focus on different aspects and points of the design process and offer insights on different aspects of uncertainty. The research presented in this paper describes the manifestation of uncertainty and proposes a classification. The classification consists of context uncertainty arising from the situation circumstances, data uncertainty stemming from input information or data into a further process, model uncertainty resulting from the simplifications in models, and phenomenological uncertainty connected to the outcome of a process. Each of these categories is described in detail offering a basis for positioning specific research contributions published in previous ICED conferences. This offers a basis for the consideration of the appropriate uncertainty management methods.

Keywords: uncertainty, uncertainty management, uncertainty classification

1 INTRODUCTION

Uncertainty has gained growing interest across different disciplines during the last decade. The International Conference on Engineering Design (ICED) has published 32 papers about uncertainty research in the past 10 years with the number growing from two papers in 2003 to 17 papers in 2009. These papers offer different insights on uncertainty in the design process with different focuses and applications.

The research presented in this paper defines uncertainty as a potential deficiency in any phase or activity of the process which can be characterized as not definite, not known or not reliable [1]. Furthermore, if uncertainty is connected to a person, it is what “causes one to feel uncertain” in the sense that it makes one feel unconfident or not sure [1]. The research presented in this paper assumes uncertainty to be a concept that does not need to be connected to a person but which can exist independently. Thus, it exists on the personal, group and organizational level and is understood as such in the presented research. Uncertainty can be both, a threat such as the probability of failure of material but also an opportunity for innovation and progress [2].

The reviewed literature about uncertainty research across different domains such as design, metrology, economics and management offers similarities and differences between the approaches. The conclusion of such a review can only be that a holistic classification of uncertainty has to be effected in layers to accommodate the different aspects. This concept was confirmed by other research approaches as presented by e.g. Walker et al. [3] who describes three dimensions as the nature, level and location of uncertainty. The nature describes how the uncertainty arises, either from inherent variability (aleatory) or from a lack of knowledge (epistemic), the level considers the severity of the uncertainty and the location establishes where the uncertainty is revealed in the model [3]. This is a useful approach in characterizing uncertainty; however it misses aspects such as the causes and the expression which are important layers to identify suitable modeling and management techniques. The causes define the source or reason and answer the question of what causes the uncertainty [4]. The expression classifies the way the uncertainty is communicated or articulated, quantitatively or qualitatively [5].

This paper focuses on the layer of the location which is described as the manifestation of uncertainty because ‘location’ suggests a physical meaning rather than the point within the process. The layer of manifestation offers the highest impact on the uncertainty occurring in the design process. Classifying

the different points in the design process to characterize the approaches described in literature offer a more effective way of modeling and managing this uncertainty within the design community. The aim of the research presented in this paper is to propose a classification of the manifestation of uncertainty to offer a basis for a shared understanding and characterization of the concept within the area of design research. This classification is based on the contribution by Walker et al. [3] who describe this aspect as location. Walker et al. described five aspects, namely context, model, inputs, parameter and model outcome. These terms contain much overlap in their meanings. For example, the term parameter can identify the input in the form of e.g. design parameters model parameters or final state operands using e.g. performance parameters [6]. Thus, the manifestations of uncertainty applied to the presented research as depicted in Figure 1 are:

- the given context of the situation of problem manifesting itself in context uncertainty
- the input into the process manifesting itself in data uncertainty,
- the model structure or development process manifesting itself in model uncertainty,
- the outcome of the modeling process manifesting itself in phenomenological uncertainty

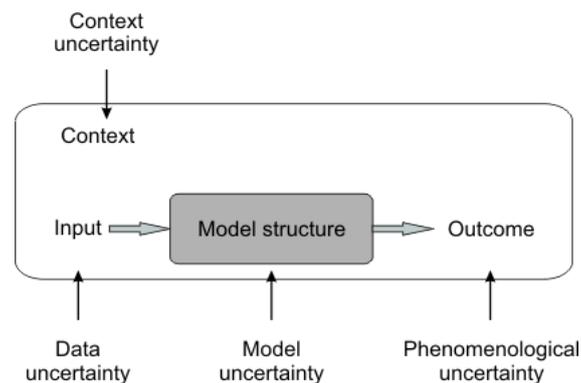


Figure 1: Manifestation of uncertainty

Sections 2-5 describe these different manifestations of uncertainty in more detail using examples. The overall benefit of the proposed classification is that it enables a positioning of research approaches described in literature in a common format for use within design research. This is exemplified by using the contributions to previous ICED conferences which are described in the suitable section.

2 CONTEXT UNCERTAINTY

The context of a situation can be defined as the circumstances that surround an event or a situation. Context uncertainty describes the potential deficiency from influence of the context on the considered system for example the level of economic instability [7]. DeWeck et al [8] distinguished two types of context uncertainty, depending on the company's control over it, endogenous (or internal) and exogenous uncertainties.

Endogenous uncertainties arise from "within" the system or product and are under the company's control [8]. It typically arises from the product context (or service context, depending on the considered project) and the corporate context. For example, Dandache and Bocquet [9] described in their paper for ICED'09 the uncertainty connected to the company's knowledge and its available technology in the context of designing. Their focus was on the loss of knowledge when outsourcing design tasks during make-or-buy decisions which may be classified as endogenous uncertainty. The company can influence these uncertainties and include them in their decision processes.

Exogenous uncertainties lie outside a company's control or influence and typically arise from the use context of the product, i.e. how it is used/operated, the market context and political and cultural context [8]. For example, Polverini et al. [10] at ICED'09 focused on product innovation processes under uncertain conditions arising from e.g. the market context in the form of international competition and the pressure to innovate. These are conditions the company cannot influence or control but has to adapt to and manage in its processes.

3 DATA UNCERTAINTY

Data uncertainty describes the uncertainty that is connected to the input into the system or model [3]. This can be connected to different types of input apart from data but the term “data uncertainty” is predominant in literature. It has also been discussed as input uncertainty [11] or design parameter uncertainty [12]. This manifestation of uncertainty can be divided into data incompleteness, data inaccuracy, and variation in the input data [13].

The *data incompleteness* can be connected to gaps in the available data in comparison to the needed data [14]. It describes the fact that some of the data that is needed in the modelling process is not available. A suitable method to deal with data uncertainty arising from data incompleteness has been described as estimation which was the focus of Adolphy et al.’s paper in ICED’09 [15]. Estimation is defined as the judgment or the “*rough calculation of the value, number, quantity, or extent of something*” [1]. It means that the gaps in the available data are filled by e.g. a comparison to known or existing products or components [16]. Especially in cost forecasting, estimation is a method applied on a regular basis [17].

Data inaccuracy can be connected to the inexactness or vagueness of the available data or the trustworthiness/reliability of the data and information in the process [3, 14]. Inexactness of data has been the topic of research especially in the area of metrology which studies the measurement of the physical components of a product. Areas such as precision engineering as described by Erbe et al. in their paper for ICED’09 [18] focused on the accuracy of measurements in the range of micrometers to reduce the impact of uncertainty. The trustworthiness of data is connected to the source of the information [19]. For example, Hitziger and Bertsche describe in their paper for ICED’05 [20] the uncertainty connected to the reuse and transfer of data from one product to another when there are differences in e.g. the geometry or load of material of the components. The authors use a transformation factor which describes the uncertainty connected to the data inaccuracy of the transferred information.

For specific situations, there might be a *variation in the data* due to the fact that different alternatives may be plausible as input values. This has also been described as input parameter uncertainty [21]. For example, the strength of a particular material can vary due to e.g. inhomogeneity or the dimensions of a physical asset may vary due to e.g. manufacturing capability [22]. This can have an impact on e.g. the modelling of the assembly of components with varying geometrical measurements. For example, Dimitrellou et al.’s paper from ICED’07 [22] focused on the description of tolerances in manufacturing assemblies to achieve a cost optimal final product.

4 MODEL UNCERTAINTY

Model uncertainty describes the inaccuracies of a model in comparison to reality [23]. It is connected to the usage of simplified relationship(s) in models to represent the “real world”, relationship(s) such as the assignment of quantities to qualitative uncertainties [24]. Model uncertainty means that model-based predictions may differ from reality [25]. It can be further classified into conceptual, mathematical, and computational model uncertainty [26].

Conceptual model uncertainty describes the simplification and inaccuracies in the model assumptions of the system comprising different processes such as the possible physical behaviour of a particular material [27]. It has also been discussed as model parameter uncertainty [6] or model structure uncertainty [28]. The simplifications can result from two different aspects [23] namely;

- a general lack of understanding which has also been named as model structure uncertainty [21], or
- by deliberate simplifications due to economy or convenience which has also been referred to as e.g. model parameter uncertainty [21].

The method of validation offers insights in the applicability of the suggested model to the specific real world situation to be modeled [29]. This usually occurs by comparing the conceptual model characteristics with the modeling objectives. This means that the model is only validated against its modeling purpose, not against its correct representation of the real world, thus, conceptual model uncertainty always exists [29].

Mathematical model uncertainty describes additional approximation or simplification of the mathematical expressions to describe the qualitative model [26]. These approximate relationships are typically called transfer functions when the conceptual model is developed into a mathematical or

computational model and are named performance functions when they relate to performance parameters [27]. An example was described in Farhangmehr et al.'s paper in ICED 2009 [30] in their description of a Capture, Assessment and Communication Tool for Uncertainty Simulation (CACTUS) method. In this method, qualitative (.i.e. unmeasurable) uncertainties are given a value by the application of importance numbers from 1 (lowest) to 4 (highest). These importance numbers are derived from expert judgment. The use of these numbers in further mathematical models may introduce mathematical model uncertainty as they suggest, that an uncertainty factor weighted e.g. 2 is twice as important as another weighed 1.

Computational model uncertainty arises during the selection of the computational method or technique [31] or the development of the computerised representation through programming and implementation [32]. To ensure the correctness of the computational program at its implementation in comparison to the conceptual model, the method of verification has been described in literature [29]. Model verification is the comparison between the numerical solution of a computerised model with either a manual calculation or an analytical solution, as described by Rajabally et al. in their paper for ICED'03 [29].

In the modelling process, these different categories of model uncertainty can be identified and reduced or managed. However, they will always be existent as the developed model is by default a simplification of the real world. For example, modelling the costs of a project including the possible uncertainty usually generates a cost forecast with a possible confidence level of no more than 95% [33], allowing a difference due to the simplifications of the cost forecasting model.

5 PHENOMENOLOGICAL UNCERTAINTY

Phenomenological uncertainty can be defined as the unpredictability of the future due to unknown events or influences [34]. For example, it can be connected to the inability of predicting the consequences of a decision in the future [35] or the possible behaviour of a considered system [36]. It is created by the fact that some relevant information may not be known at the point of formulation, sometimes even in principle which has been described as ignorance [3]. It has also been described as “unknown unknowns” and “Nature”, meaning that they cannot be foreseen or influenced [8].

These approaches in describing and managing uncertainty, particularly its influence on decision making, offer important insights in their particular area of research. However, from the reviewed literature, no classification of phenomenological uncertainty could be found. The purpose of describing and understanding phenomenological uncertainty is the reduction of avoidable surprises on the outcome of current decisions [37]. This type of uncertainty can by definition not be known or modelled completely as there may always be the influence of an unexpected event. However, the aim of uncertainty management is to identify, describe and, therefore, be aware of important possible phenomenological uncertainties that may influence the outcome of an uncertain problem or situation. Possibility approaches attempt to model this uncertainty by the degree of surprise [38].

Important areas of research that are influenced by phenomenological uncertainty are for example decision making and robust design. The next two sub-sections further describe these approaches.

5.1 Uncertainty in decision making

One area, where phenomenological uncertainty is of importance is decision making, particularly when it is connected to innovation and development processes of new products. For example, Gutierrez et al. evaluate in their paper from ICED'09 [39] the quality of new product ideas during the selection process. This is highly influenced by uncertainty, in particular phenomenological uncertainty as the accuracy of this evaluation process and the outcome of the implementation of the “good idea” are not known until the product is launched. Gutierrez et al. focus on new product ideas that influence the future competitive position of the company which means that they have a high impact on the company's business in addition to being highly uncertain.

Another example for the evaluation of novel products in the decision making process is the research described by Kota and Chakrabarti in their paper for ICED'09 [40]. The evaluation of product ideas and alternatives can only occur to a limited level of confidence in the form of the most likely performance, most likely cost, most likely environmental impacts and so on. All of these estimates can be wrong due to e.g. unforeseen events. Kota and Chakrabarti focus on the trade-off analysis between different design alternatives where the consideration of the different evaluation criteria such as performance or cost may be uncertain. The authors argue that these criteria can only be estimated with

limited confidence, thus, there is always a level of uncertainty connected to them. The influence of phenomenological uncertainty may change the relative evaluation of the design alternatives [40]. Connected to the area of decision maker under uncertainty is the formulation of a belief about the different possible future events [34]. This means that even though the occurrence of future events is not known, the decision maker may still be able to assign a subjective likelihood to this event and base the decision on this, Connected areas of research are the level of optimism [41] and regret [42] in a decision maker.

5.2 Robustness against phenomenological uncertainty

Another area influenced by the existence of phenomenological uncertainty is research into the robustness of e.g. processes or products. One example is the ICED'07 contribution by Chalupnik et al. [43] which analyses the robustness of a design process towards uncertainty and unexpected adverse factors. These may influence the delivery of the expected results in the estimated time, i.e. cause the project to be delayed or not on target. The authors discuss the influence the design process structure, such as the organization of the information flow, has on the robustness of a design process against unexpected factors.

The robustness of a product design is the focus of the ICED'07 contribution by Padulo et al. [44]. According to this study, a robust product design shows minimal sensitivity to different factors such as the operation environment including weather conditions. The authors describe an approach for including the possible phenomenological uncertainties in the product design and, thus, make the product more robust against these influences.

Studies focusing on the robustness of e.g. a process or a product are usually aimed at the reduction of the impact of phenomenological uncertainty. Thus, these contributions usually do not offer insights on e.g. the structure of the uncertainty. However, the authors of this paper propose that the classification of uncertainty proposed by their research may support the design of robustness in products or processes.

6 PROPOSED CLASSIFICATION

The classification proposed by the authors for the manifestation of uncertainty, i.e. for the consideration of the point of occurrence within the design process is depicted in Figure 2. The manifestation was described according to the points of occurrence in the process, namely context, data, model and phenomenological uncertainty with sub-classifications described for each category.

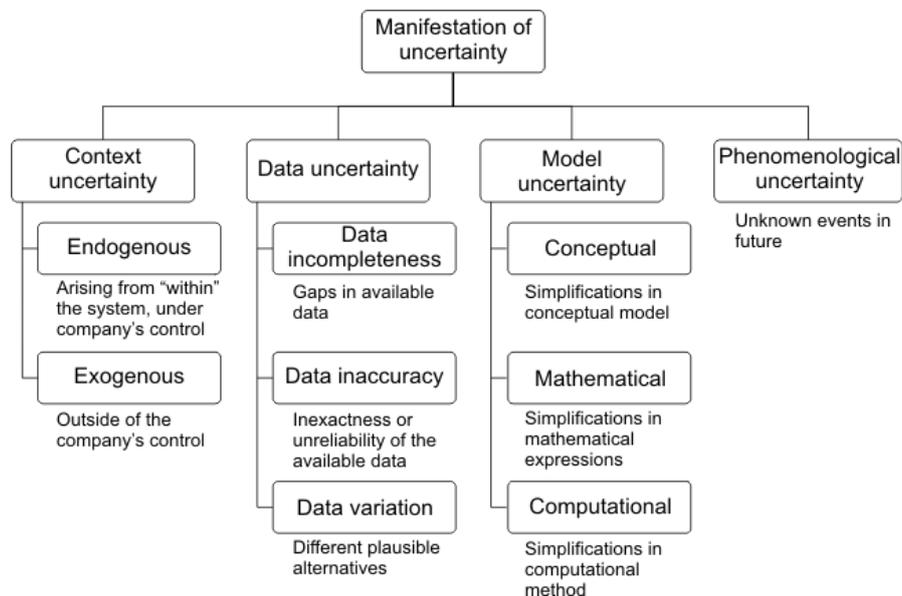


Figure 2: Proposed classification for manifestation of uncertainty

This classification was primarily derived from literature focusing on uncertainty, particularly in the areas of engineering, economics and decision making. It is the authors' opinion that approaches and terms adopted by other researchers can be integrated in the proposed classification. However, some

approaches may offer further insights into specific areas to achieve a more detailed description of particular aspects of this classification. For example, deWeck et al.'s [8] paper on context uncertainty describes the different categories within the classification of endogenous and exogenous uncertainty. This paper does not focus on this level of details of the different categories of uncertainty manifestation.

Furthermore, this classification of the uncertainty manifestation focuses on the point in the design process where the uncertainty occurs. It does not describe its nature, the cause for this uncertainty, its level of severity or its expression. These are the remaining four levels of uncertainty which have not been discussed in this paper. For a holistic characterization of uncertainty, these would have to be considered in addition to the manifestation of uncertainty.

The proposed classification allows the positioning of specific research contributions within the process and the consideration of the appropriate uncertainty management methods. The next section exemplifies this by positioning the contributions of previous ICED conferences on the topic of uncertainty.

7 CLASSIFICATION OF ICED CONTRIBUTIONS

To illustrate the application of the proposed classification the thirty four papers published in ICED proceedings from 2003 to 2009 (the proceedings of 2003 contained the first paper on uncertainty research in the ICED community) have been used to illustrate the approach. Table 1 offers an overview of the main areas of contribution. The contributions are ordered alphabetically of the first author's name, thus, the order is not to be seen as an indication for the importance of the papers.

Table 1: Classification of ICED contributions according to their manifestation of uncertainty

Manifestation	Sub-classifications	ICED contributions
Context uncertainty	Endogenous	Chalupnik et al. "Approaches to Mitigate the Impact of Uncertainty in Development Processes" ICED'09. Dandache and Bocquet "A General Management System for Design Outsourcing" ICED'09. Daniel et al. "Uncertainty Management in Innovative Product Design" ICED'07. DeWeck et al. "A classification of Uncertainty for Early Product and System Design" ICED'07.
	Exogenous	Chalupnik et al. "Approaches to Mitigate the Impact of Uncertainty in Development Processes" ICED'09. Daniel et al. "Uncertainty Management in Innovative Product Design" ICED'07. DeWeck et al. "A classification of Uncertainty for Early Product and System Design", ICED'07. Gorbea et al. "Innovation and Vehicle Architecture Development in a New Age of Architectural Competition" ICED'09. Moon et al. "Universal Product Platform and Family Design for Uncertain Market" ICED'09. Polverini et al. "Supporting Product Innovation in Uncertainty Conditions: A u-sDSP Based Decision Making Approach" ICED'09.
Data uncertainty	Data incompleteness	Adolphy et al. "Estimation and its Role in Engineering Design – An Introduction" ICED'09. Saravi et al. "Estimating Cost and Improving Trade-off between Performance and Cost et the Early Design Stages" ICED'09.
	Data inaccuracy	Erbe et al. "Optimizing of Heterogenous Systems by Adaptation of Function Typology" ICED'09. Hitziger and Bertsche "Contribution to an Optimized Development Process for Model Range Products Considering Uncertainty of Information" ICED'05.
	Data variation	Dimitrellou et al. A Systematic Approach for Cost Optimal

		<p>Tolerance Design” ICED’07.</p> <p>Kloberdanz et al. “Process Based Uncertainty Analysis – An Approach to Analyze Uncertainties Using a Process Model” ICED’09.</p>
Model uncertainty	Conceptual	<p>Engelhardt et al. “Uncertainty-Mode- and Effects-Analysis – An Approach to Analyze and Estimate Uncertainty in the Product Life Cycle” ICED’09.</p> <p>Rajabally et al. Combining Evidence to Justify the Appropriate Use of Models in Engineering Design” ICED’03.</p>
	Mathematical	<p>Farhangmehr et al. “Optimal Risk-based Integrated Design (ORBID) for Multidisciplinary Complex Systems” ICED’09.</p> <p>Padulo et al. “Comparative Analysis of Uncertainty Propagation Methods for Robust Engineering Design” ICED’07.</p>
	Computational	<p>Goh et al. “A Framework for the Handling of Uncertainty in Engineering Knowledge Management to Aid Product Development” ICED’05.</p> <p>Rajabally et al. Combining Evidence to Justify the Appropriate Use of Models in Engineering Design” ICED’03.</p>
Phenomenological uncertainty		<p>Ariel and Reich “Improving the Robustness of Multicriteria Decision Making” ICED’03.</p> <p>Chalupnik et al. “Understanding Design Process Robustness: A Modelling Approach” ICED’07.</p> <p>Gerber “Prototyping: Facing Uncertainty through Small Wins” ICED’09.</p> <p>Goh et al. “Strategies to Enhance Design Analysis Reuse: A Case Study in Uncertainty” ICED’07.</p> <p>Gutierrez et al. “What’s a good idea? Understanding Evaluation and Selection of New Product Ideas” ICED’09.</p> <p>Jahn and Binz “A Highly Flexible Project Majority Management Method for the Early Phase of Product Development” ICED’09.</p> <p>Kota and Chakrabarti “A Method for Comparative Evaluation of Product Life Cycle Alternatives Under Uncertainty” ICED’07.</p> <p>Kota and Chakrabarti “Development of a Method for Estimating Uncertainty in Evaluation of Environmental Impacts During Design” ICED’07.</p> <p>Kota and Chakrabarti “A Method for Evaluating of Product Lifecycle Alternatives under Uncertainty” ICED’09.</p> <p>Kreye et al. “Uncertainty in Through Life Costing within the Concept of Product Service Systems: A Game Theoretic Approach” ICED’09.</p> <p>O’Donovan et al. “Signposting: Modelling Uncertainty in Design Processes” ICED’03.</p> <p>Padulo et al. “Comparative Analysis of Uncertainty Propagation Methods for Robust Engineering Design, ICED’07.</p> <p>Snape et al. “Margins of Performance in Engineering: The Requirement for a Systematic Approach” ICED’05.</p> <p>Tauhid and Okudan “Fuzzy Information Axiom Approach for Design Concept Evaluation” ICED’07.</p>

Table 1 shows all the ICED publications that present results and findings on the topic of uncertainty research. Some papers are mentioned in multiple categories of the manifestation of uncertainty because they model the different aspects. For example, Chalupnik et al. [43] discuss the influence of both endogenous and exogenous context uncertainty on the design process.

8 CONCLUSIONS

The research presented in this paper proposes a classification for the manifestation of uncertainty which defines context, data, model and phenomenological uncertainty. An exemplary positioning of different research contribution was presented in the form of previous ICED conference papers. This classification constitutes one of five layers of uncertainty (the other four are: nature, cause, level and expression of uncertainty) which offer a holistic description of the uncertainty inherent in a situation.

The presented classification can impact uncertainty research and application of methods of uncertainty formalism in the different disciplines such as design but also metrology, economics and management. The different research contributions can be positioned in the five layers of uncertainty classification which shows their similarities and differences. This can form the basis of effective uncertainty modeling and management. By comparing the identified combination of uncertainty characteristics with the characteristics of previously described research in literature, suitable modeling and management techniques can be identified.

However, this holistic classification and the process of identifying suitable modeling and management techniques are outside of the scope of this paper. The research presented in this paper describes one of the layers and, thus, one of the aspects of this holistic description of uncertainty. It is thus to be seen as one part of the puzzle of uncertainty.

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