MANIFESTATION OF UNCERTAINTY - A CLASSIFICATION

Melanie E. Kreye [1], Yee Mey Goh [2] and Linda B. Newnes [1]
(1) University of Bath, UK (2) Loughborough University, UK

ABSTRACT
Different approaches of uncertainty described in literature focus on different aspects and points of the design process and offer insights on different aspects. The aim of this paper is to propose a classification of the manifestation of uncertainty describing the different points of the design process which offers a basis for a shared understanding and characterization of uncertainty. The classification consists of context uncertainty arising from the situation circumstances, data uncertainty stemming from input information or data, model uncertainty resulting from the simplifications in models, and phenomenological uncertainty connected to the outcome of the process. Each of these categories is described in detail which offers the basis for positioning the research contributions published in previous ICED conferences. The classification allows an identification of the part of the design process which is most influenced by uncertainty and activities for improvement and uncertainty reduction can be focused at this aspect. Furthermore, techniques for modeling and managing this uncertainty can be identified.

Keywords: uncertainty, uncertainty management, uncertainty classification

1 INTRODUCTION

Uncertainty has gained growing interest across different disciplines and particularly within the design community. 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 main challenge of uncertainty in design is that different types of uncertainty can occur at different stages of the design process. These different uncertainties can require distinctive handling and modeling techniques to understand their influence and importance.

The aim of this paper is to ascertain a common approach to classify uncertainty across various domains, particularly for the point within the design process at which the uncertainty occurs. This is described as the manifestation of uncertainty. For example, the decision made about the material used for a particular product part, the assumptions made about the customer’s use of the product, simplifications made in the modeling process or unknown influences during the products life cycle can influence the design activity in fundamentally different ways. This paper proposes an approach to identify the differences to enable effective management of the uncertainty.

The overall benefit of the proposed classification is that it enables a positioning of research approaches described in literature into a common format for use within design research. This is exemplified by using the contributions to previous ICED conferences. The manifestation of uncertainty in design offers important insights because the whole process can be broken down and thus considered more effectively. This allows an identification of the part of the design process which is most influenced by uncertainty and activities for improvement and uncertainty reduction can be focused at this aspect. Furthermore, techniques for modeling and managing this uncertainty such as probability theory, fuzzy set theory, Delphi method, and possibility theory can be positioned within the proposed classification which offers a basis for the identification of a suitable technique to model or manage the uncertainty connected to a particular design aspect.

The proposed classification allegorizes one layer of a holistic classification of uncertainty research which defines five layers. The next section offers a short introduction to this holistic classification and positions the manifestation of uncertainty within it. The main focus of this paper is on the layer of manifestation of uncertainty; however to provide the context of the reported research, the holistic uncertainty classification is described.

2 UNCERTAINTY CLASSIFICATION

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 here also 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. Uncertainty can be both, a threat such as the probability of failure of material or an opportunity for innovation and progress [2].

2.1 Five layers of uncertainty

The presented classification is based on a literature review in the area of uncertainty research, particularly on uncertainty modeling across different domains such as design, metrology, economics and management. This offered insights into the similarities and differences between the approaches. The conclusion of such a review is that a holistic classification of uncertainty has to be effected in layers to accommodate the different aspects. For example, the approaches differentiate between quantitative and qualitative uncertainty [3], aleatory and epistemic uncertainty [4] or exogenous uncertainty [5]. The concept of uncertainty layers was confirmed by other research approaches as presented by e.g. Walker et al. [6] who describe three dimensions, the nature, level and location of uncertainty.

The nature describes the characteristics of the uncertainty, in other words if it is the inherent variability (aleatory uncertainty) or a general lack of knowledge (epistemic uncertainty). For example, the measurement of a particular part of the product may vary due to inaccuracies of the manufacturing machine (aleatory) or because the precise value has not yet been specified in the design (epistemic). The levels express the severity of the considered uncertainty, i.e. the amount of information available and the amount of information missing for a certain description of the situation [7]. The location establishes where the uncertainty is revealed in the model [6].

This is a useful approach in characterizing uncertainty; however it misses aspects such as the causes and the expression which are important additional layers for identifying suitable modeling and management techniques. The causes define the source or reason and answer the question of what causes the uncertainty [8]. The expression classifies the way the uncertainty is communicated or articulated, either quantitatively or qualitatively [3]. The importance of these two additional layers of uncertainty has been highlighted in literature [3, 8, 9]. Thus, a holistic uncertainty classification constitutes five layers as described in Table 1.

Table 1: Classifying uncertainty into five layers

Layer	Description	Further references
Nature	the general characteristics of the uncertainty, in other words if it is the inherent variability (aleatory uncertainty) or a general lack of knowledge (epistemic uncertainty).	[3], [10], [11]
Cause	the reason or source of the uncertainty. In general, uncertainty can be caused by a lack of understanding, ambiguity and human behavior with different sub-categories within each of these three causes.	[12], [13], [14]
Level	the severity of the uncertainty, i.e. the amount of information available and the amount of information missing for a certain description of the situation.	[7], [15]
Manifestation	the point of the process where the uncertainty occurs.	[6], [5], [16], [17]
Expression	the way the uncertainty is articulated or communicated. It can be quantitative (measurable) or qualitative (unmeasurable).	[3], [18], [19]

One of the presented five layers constitutes the manifestation of uncertainty. This is the main focus of this paper and the classification of this paper is introduced in the next section.

2.2 Manifestation of uncertainty

This paper proposes a classification of the manifestation of uncertainty which is based Walker et al.’s ‘location’. The term was changed because ‘location’ suggests a physical meaning rather than the point

within the process. Walker et al. [6] described five aspects, namely context, model, inputs, parameter and model outcome. These terms contain much overlap in their meanings and in the way they have been described in other approaches. For example, the term parameter can identify the original state operands such as input data or design parameters, using simplifications such as model parameters or derive the final state operands using e.g. performance parameters [20]. Thus, the use of parameter uncertainty is very ambiguous and does not offer a basis for a holistic classification or characterization.
Furthermore, the classification described by Walker et al. does not consider the uncertainty connected to future events such as implications that today's decisions have on future opportunities or influences during the products life cycle and their impact at the design stage [21]. This aspect is indicated by Walker et al.'s 'model outcome', however, the authors do not consider the uncertainty that can influence long term implications such as the accuracy of estimates or forecasts or the use of the designed product.
The presented classification offers a basis for a shared understanding and characterization of the concept within the area of design research.

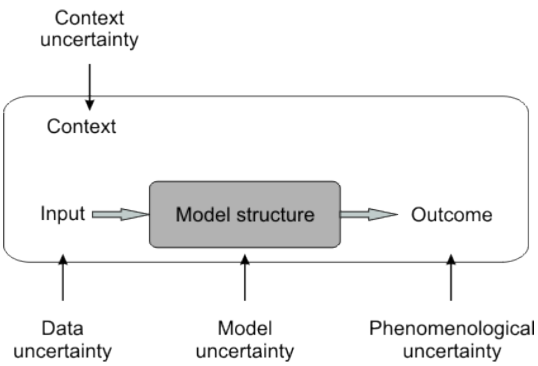

Figure 1: Manifestation of uncertainty

The classification of the manifestation of uncertainty as depicted in Figure 1 are:

- the given context of the situation of problem manifesting itself in context uncertainty
- the input into the process such as design parameters manifesting itself in data uncertainty,
- the model structure or model parameters manifesting itself in model uncertainty, the outcome of the modeling process or performance of the considered system manifesting itself in phenomenological uncertainty

Sections 3-6 describe these different manifestations of uncertainty in more detail using examples.

3 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 [22]. DeWeck et al [5] 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 [5]. It typically arises from the product context (or service context, depending on the considered project) and the corporate context. For example, Dandache and Bocquet [23] 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 [5]. For example, Polverini et al. [24] 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.

4 DATA UNCERTAINTY

Data uncertainty describes the uncertainty that is connected to the input into the system or model [6]. 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 [25] or design parameter uncertainty [26]. This manifestation of uncertainty can be divided into data incompleteness, data inaccuracy, and variation in the input data [9].

The ***data incompleteness*** can be connected to gaps in the available data in comparison to the needed data [27]. 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 [28]. 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 [29]. Especially in cost forecasting, estimation is a method applied on a regular basis [30].

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 [6, 27]. 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 [31] 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 [32]. For example, Hitziger and Bertsche describe in their paper for ICED'05 [33] 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 [34]. 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 [35]. 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 [35] focused on the description of tolerances in manufacturing assemblies to achieve a cost optimal final product.

5 MODEL UNCERTAINTY

Model uncertainty describes the inaccuracies of a model in comparison to reality [16]. 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 [36]. Model uncertainty means that model-based predictions may differ from reality [37]. It can be further classified into conceptual, mathematical, and computational model uncertainty [38].

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 [39]. It has also been discussed as model parameter uncertainty [20] or model structure uncertainty [21]. The simplifications can result from two different aspects [16] namely;

- a general lack of understanding which has also been named as model structure uncertainty [34], or
- by deliberate simplifications due to economy or convenience which has also been referred to as e.g. model parameter uncertainty [34].

The method of validation offers insights in the applicability of the suggested model to the specific real world situation to be modeled [40]. 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 [40].

Mathematical model uncertainty describes additional approximation or simplification of the mathematical expressions to describe the qualitative model [38]. 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 [39]. An example was described in Farhangmehr et al.'s paper in ICED 2009 [41] 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 [42] or the development of the computerised representation through programming and implementation [43]. 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 [40]. 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 [40].

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% [44], allowing a difference due to the simplifications of the cost forecasting model.

6 PHENOMENOLOGICAL UNCERTAINTY

Phenomenological uncertainty can be defined as the unpredictability of the future due to unknown events or influences [17]. For example, it can be connected to the inability of predicting the consequences of a decision in the future [45] or the possible behaviour of a considered system [46]. 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 [6]. It has also been described as "unknown unknowns" and "Nature", meaning that they cannot be foreseen or influenced [5].

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 [47]. 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 [15].

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.

6.1 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 [48] 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 [49]. 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 [49].
Connected to the area of decision maker under uncertainty is the formulation of a belief about the different possible future events [17]. 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 [50] and regret [51] in a decision maker.

6.2 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. [52] 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. [53]. 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.

7 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.

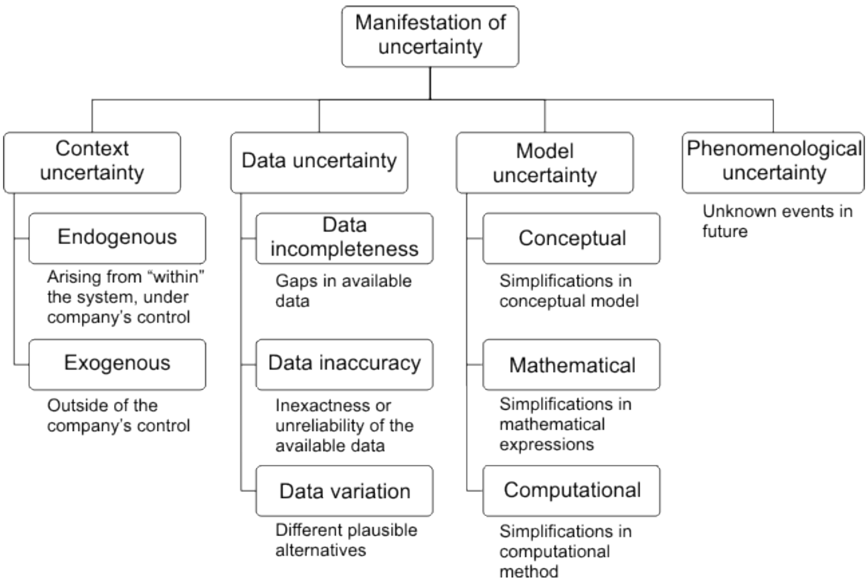

Figure 2: Proposed classification for manifestation of uncertainty

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 [5] 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.

8 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 2 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 2: 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 Tolerance Design” ICED’07. Kloberdanz et al. “Process Based Uncertainty Analysis – An Approach to Analyze Uncertainties Using a Process Model” ICED’09.
Model uncertainty	Conceptual	Engelhardt et al. “Uncertainty-Mode- and Effects-Analysis – An Approach to Analyze and Estimate Uncertainty in the Product Life Cycle” ICED’09. Rajabally et al. Combining Evidence to Justify the Appropriate Use of Models in Engineering Design” ICED’03.
	Mathematical	Farhangmehr et al. “Optimal Risk-based Integrated Design (ORBID) for Multidisciplinary Complex Systems” ICED’09. Padulo er al. “Comparative Analysis of Uncertainty Propagation Methods for Robust Engineering Design” ICED’07.
	Computational	Goh et al. “A Framework for the Handling of Uncertainty in Engineering Knowledge Management to Aid Product Development” ICED’05. Rajabally et al. Combining Evidence to Justify the Appropriate Use of Models in Engineering Design” ICED’03.
Phenomeno-logical uncertainty		Ariel and Reich “Improving the Robustness of Multicriteria Decision Making” ICED’03. Chalupnik et al. “Understanding Design Process Robustness: A Modelling Approach” ICED’07. Gerber “Prototyping: Facing Uncertainty through Small Wins” ICED’09. Goh et al. “Strategies to Enhance Design Analysis Reuse: A Case Study in Uncertainty” ICED’07. Gutierrez et al. “What’s a good idea? Understanding Evaluation and Selection of New Product Ideas” ICED’09. Jahn and Binz “A Highly Flexible Project Majurity Management Method for the Early Phase of Product Development” ICED’09. Kota and Chakrabarti “A Method for Comparative Evaluation of Product Life Cycle Alternatives Under Uncertainty” ICED’07. Kota and Chakrabarti “Development of a Method for Estimating Uncertainty in Evaluation of Environmental Impacts During Design” ICED’07. Kota and Chakrabarti “A Method for Evaluating of Product Lifecycle Alternatives under Uncertainty” ICED’09. Kreye et al. “Uncertainty in Through Life Costing within the Concept of Product Service Systems: A Game Theoretic Approach” ICED’09. O’Donovan et al. “Signposting: Modelling Uncertainty in Design Processes” ICED’03. Padulo et al. “Comparative Analysis of Uncertainty Propagation Methods for Robust Engineering Design, ICED’07. Snape et al. “Margins of Performance in Engineering: The Requirement for a Systematic Approach” ICED’05. Tauhid and Okudan “Fuzzy Information Axiom Approach for Design Concept Evaluation” ICED’07.

Table 2 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. [52] discuss the influence of both endogenous and exogenous context uncertainty on the design process.

9 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. Similarly, other approaches to uncertainty research described in literature can be positioned within the presented classification which identifies their similarities and differences. This forms the basis of a shared understanding of the manifestation of uncertainty within research.

The presented classification constitutes one of five layers of uncertainty (the other four are: nature, cause, level and expression of uncertainty). Following a similar process of positioning research contributions within all five layers offers a holistic description of the uncertainty inherent in a situation. This can form the basis of effective uncertainty modeling and management.

Future research objectives include the application of the presented classification on different approaches described in literature to obtain a ‘database’ of the use of different uncertainty modeling techniques. Based on this ‘database’, a suitable modeling technique can be chosen. Certain techniques may be useful for a specific type of uncertainty. For example, probability based techniques may offer insights particularly for variation in the available data. Further research has to be done to identify these connections. However, the process of identifying suitable modeling and management techniques and a more detailed analysis of the holistic uncertainty classification in five layers 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.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the Innovative Design and Manufacturing Research Centre (IdMRC) at University of Bath, UK funded by the Engineering and Physical Science Research Council (EPSRC) under Grant No. GR/R67507/01 for the research reported in this paper.

REFERENCES

[1] C. Soanes, "The Oxford English Dictionary". Vol. XI, 2005 (Oxford University Press, Oxford, UK).

[2] D.G. Ullmann. "Design: The Evolution of Information Punctuated by Decisions". In *ICED'09 - International Conference on Engineering Design*. Stanford, Ca, USA, 2009, 24-27 August.

[3] J.P. Van der Sluijs; M. Craye; S. Funtowicz; P. Kloprogge; J. Ravetz; and J. Risbey, "Combining Quantitative and Qualitative Measures of Uncertainty in Model-Based Environmental Assessment: The NUSAP System". *Risk Analysis: An International Journal*, 2005, 25(2), pp. 481-492.

[4] B. Moeller and M. Beer, "Engineering computation under uncertainty – Capabilities of non-traditional models". *Computers and Structures*, 2008, 86(2008), pp. 1024-1041.

[5] O. de Weck; C. Eckert; and J. Clarkson. "A Classification of Uncertainty for Early Product and System Design". In *ICED'07 - International Conference on Engineering Design*. Paris, France, 2007, 28-31 August 2007.

[6] W.E. Walker; P. Harremoes; J. Rotmans; J.P. Van der Sluijs; M.B.A. Van Asselt; P. Janssen; and K.V. Krauss, "Defining uncertainty: a conceptual basis for uncertainty management in model based decision support". *Integrated Assessment* 2003, 4(1), pp. 5-17.

[7] H. Courtney, "20/20 Foresight: Crafting Strategy in an Uncertain World ". 2001 (Harvard Business School Press,

[8] L.E. García-Fernández and M. Garijo, "Modeling Strategic Decisions Using Activity Diagrams to Consider the Contribution of Dynamic Planning in the Profitability of Projects Under Uncertainty". *IEEE - Transactions on Engineering Management*, 2010, 57(3), pp. 463-476

[9] M.A.J. Huijbregts; G. Norris; R. Bretz; A. Ciroth; B. Maurice; B. von Bahr; B. Weidema; and A.S.H. de Beaufort, "Framework for modelling data uncertainty in life cycle inventories". *The International Journal of Life Cycle Assessment*, 2001, 6(3), pp. 127-132.

[10] W.L. Oberkampf; S.M. DeLand; B.M. Rutherford; K.V. Diegert; and K.F. Alvin, "Error and uncertainty in modeling and simulation". *Reliability Engineering and System Safety*, 2002,

75(2002), pp. 333-357.
[11] B. Krzykacz-Hausmann, "An approximate sensitivity analysis of results from complex computer models in the presence of epistemic and aleatory uncertainties". *Reliability Engineering & System Safety*, 2006, 91(10-11), pp. 1210-1218.
[12] D.P. Thunnissen. "Uncertainty Classification for the Design and Development of Complex Systems". In *PMC2003 - 3rd Annual Predictive Methods Conference*. Newport Beack, California, USA, 2003, 16-17 June.
[13] P. Ghirardato; F. Maccheroni; and M. Marinacci, "Revealed Ambiguity and Its Consequences: Updating", in *Advances in Decision Making Under Risk and Uncertainty*, 2008, (Springer-Verlag, Berlin-Heidelberg), pp. 3-18.
[14] A. Morone and P. Morone, "Guessing Games and People Behaviours: What Can We Learn?", in *Advances in Decision Making Under Risk and Uncertainty*, 2008, (Springer Verlag, Berlin Heidelberg).
[15] Y.M. Goh; C.A. McMahon; and J.D. Booker, "Development and characterisation of error functions in design". *Research in Engineering Design*, 2007, 18(3), pp. 129-149.
[16] T. Nilsen and T. Aven, "Models and model uncertainty in the context of risk analysis". *Reliability Engineering and System Safety*, 2003, 79(2003), pp. 309-317.
[17] M. Abdellaoui and J.D. Hey, "Advances in Decision Making Under Risk and Uncertainty". 2008 (Springer-Verlag, Berlin-Heidelberg).
[18] D. Moens and D. Vandepitte, "Non-probabilistic approaches for non-deterministic dynamic FE analysis of imprecisely defined structures", In *ISMA2004 - International Conference on Noise and Vibration Engineering*(Editor^Editors). 2004: Leuven, Belgium. pp. 3095-3120.
[19] D. Dubois; H. Fargier; and R. Sabbadin. "Qualitative Decision Rules under Uncertainty". In *ECSQARU - 7th European Conference on Symbolic and Quantitative Approaches to Reasoning with Uncertainty* Aalborg, Denmark 2003, 2-5 July.
[20] S.S. Isukapalli "Uncertainty Analysis of Transport-Transformation Models", 1999, State University of New Jersey, Chemical and Biochemical Engineering.
[21] J.C. Refsgaard; J.P. van der Sluijs; J. Brown; and P. van der Keur, "A framework for dealing with uncertainty due to model structure error". *Advances in Water Resources*, 2006, 29(11), pp. 1586-1597.
[22] K. Grebici; Y.M. Goh; and C. McMahon. "Uncertainty and Risk Reduction in Engineering Design Embodiment Processes ". In *Design 2008*. Dubrovnik, Croatia, 2008, 19-22 May.
[23] M.R. Dandache and J.C. Bocquet. "A General Management System for Design Outsourcing". In *ICED09 - International Conference on Engineering Design*. Stanford, CA, USA, 2009, 24-27 August.
[24] D. Polverini; S. Graziosi; and F. Mandorli. "Supporting Product Innovation in Uncertainty Conditions: A U-SDSP Based Decision Making Approach". In *ICED09 - International Conference on Engineering Design*. Stanford, CA, USA, 2009, 24-27 August.
[25] S.E. Chick, "Input Distribution Selection for Simulation Experiments: Accounting for Input Uncertainty". *Operations Research*, 2001, 49(5), pp. 744-758.
[26] X.F. Sun; H.Y. Zhang; and Y.Z. Fan, "Recursive dual-linear-programming approach for parameter-uncertainty-interval estimation". *IEE Proceedings -- Control Theory & Applications*, 2003, 150(3), pp. 303.
[27] D. Hastings and H. McManus. "A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems". In *MIT Engineering Systems Symposium*. Cambridge, Massachusetts, 2004, March 2004.
[28] S. Adolphy; K. Gericke; and L. Blessing. "Estimation and its Role in Engineering Design - An Introduction". In *ICED'09 - International Conference on Engineering Design*. Stanford, California, USA, 2009, 24-27 August.
[29] A. Niazi; J.S. Dai; S. Balabani; and L. Seneviratne, "Product Cost Estimation: Technique Classification and Methodology Review". *Journal of Manufacturing Science and Engineering*, 2006, 128(2006), pp. 563-575.
[30] M.E. Saravi; L.B. Newnes; A. Mileham; and Y.M. Goh. "Estimating Cost and Improving Trade-off between Performance and Cost at the Early Design Stages". In *ICED 09 - International Conference on Engineering Design*. Stanford, USA, 2009, 24-27 August.
[31] T. Erbe; A. Frank; and R. Theska. "Optimizing of Heterogeneous Systems by Adaptation of

Function Topology". In *ICED09 - International Conference on Engineering Design*. Stanford, CA, USA, 2009, 24-27 August.
[32] P. Walley, "Statistical Reasoning with Imprecise Probabilities". 1991 (Chapman and Hall, London, UK).
[33] T. Hitziger and B. Bertsche. "Controbution to an Optimized Development Process for Model Range Products Considering Uncertainty of Information". In *ICED05 - International Conference on Engineering Design*. Melbourne, Australia, 2005, 15-18 August.
[34] X. Du and W. Chen, "A Methodology for Managing the Effect of Uncertainty in Simulation-Based Design". *AIAA Journal*, 2000, 38(8), pp. 1-36.
[35] S.C. Dimitrellou; S.C. Diplaris; and M.M. Sfantsikopouls. "A Systematic Approach for Cost Optimal Tolerance Design". In *ICED07 - International Conference on Engineering Design*. Paris, France, 2007, 28-31 August.
[36] M.J. Scott, "Quantifying uncertainty in multicriteria concept selection methods". *Research in Engineering Design*, 2007, 17(2007), pp. 175–187.
[37] D.A. DeLaurentis "A Probabilistic Approach to Aircraft Design Emphasizing Stability and Control Uncertainties", 1998, Georgia Institute of Technology, School of Aerospace Engineering.
[38] E. Zio and G.E. Apostolakis, "Two methods for the structured assessment of model uncertainty by experts in performance assessments of radioactive waste repositories". *Reliability Engineering & System Safety*, 1996, 54(2-3), pp. 225-241.
[39] Y.M. Goh "The Incorporation of Uncertainty into Engineering Knowledge Managament", 2005, University of Bristol, Department of Mechanical Engineering.
[40] E. Rajabally; P. Sen; S. Whittle; and J. Dalton. "Combining Evidence to Justify the Appropriate Use of Models in Engineering Design". In *ICED03 - International Conference on Engineering Design*. Stockholm, Sweden, 2003, 19-21 August.
[41] F. Farhangmehr and I.Y. Tumer. "Optimal Risk-based Integrated Design (ORBID) for Multidisciplinary Complex Systems". In *ICED'09 - 17th International Conference on Engineering Design*. Stanford, USA, 2009, 24-27 August.
[42] F. Rieg and F. Koch. "Selection of Finite Elements Considering Loadcases and Geometry". In *ICED'01 - International Conference on Engineering Design*. Glasgow, UK, 2001, 21-23 August.
[43] W.L. Oberkampf; S.M. DeLand; B.M. Rutherford; K.V. Diegert; and K.F. Alvin, "A New Methodology for the Estimation of Total Uncertainty in Computaional Simulation". *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 1999, 4(1999), pp. 3061-3083.
[44] A.S. Tay and K.F. Wallis, "Density Forecasting: A Survey". *Journal of Forecasting*, 2000, 19(4), pp. 235-254.
[45] J. Chen; R.R. Reilly; and G.S. Lynn, "The Impacts of Speed-to-Market on New Product Success: The Moderating Effects of Uncertainty". *IEEE Transactions on Engineering Management*, 2005, 52(2), pp. 199-212.
[46] R. Melchers, "Structural Reliability Analysis and Prediction". 2nd ed, 1999 (John Wiley & Sons, Chichester, UK).
[47] J.A. Dewar, "Assumption-based Planning: A Tool for Reducing Avoidable Surprises". 2002 (Cambridge University Press, Cambridge, UK).
[48] E. Gutierrez; I. Kihlander; and J. Eriksson. "What's a good idea? Understanding Evaluation and Selection of New Product Ideas". In *ICED09 - International Conference on Engieering Design*. Stanford, CA, USA, 2009, 24-27 August.
[49] S. Kota and A. Chakrabarti. "A Method for Evaluating of Product Lifecycle Alternatives under Uncertainty". In *ICED'09 - International Conference on Engineering Design*. Stanford University, San Francisco, USA, 2009,
[50] M.E.P. Seligman, "Learned optimism: How to change your mind and your life". 2006 (Vintage Books, New York, USA).
[51] D.E. Bell, "Disappointment in Decision Making under Uncertainty". *Operations Research*, 1985, 33(1), pp. 1-27.
[52] M.J. Chalupnik; D.C. Wynn; C. Eckert; and P.J. Clarkson. "Understanding Design Process Robustness: A Modelling Approach". In *ICED07 - International Conference on Engineering*

Design. Paris, France, 2007, 28-31 August.
[53] M. Padulo; M.S. Campobasso; and M.D. Guenov. "Comparative Analysis of Uncertainty Propagation Methods for Robust Engineering Design". In *ICED07 - International Conference on Engineering Design*. Paris, France, 2007, 28-31 August.

Contact: Melanie E. Kreye
Institution/University: University of Bath, UK
Department: Mechanical Engineering
Street: Claverton Down
Postal Code, City: BA2 7AY, Bath
Country: UK
Phone: +44 (0)1225 385366
Fax: +44 (0)1225 386928
E-mail Address: m.kreye@bath.ac.uk

Melanie Kreye is a PhD candidate at the University of Bath, UK. Her research focuses on uncertainty in pricing decisions of competitive bidding for service contracts.