ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

IDENTIFYING UNCERTAINTIES WITHIN STRUCTURAL COMPLEXITY MANAGEMENT

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ABSTRACT

Structural complexity management (StCM) is an established methodology to manage complexity within engineering design. Complexity management is necessary if complexity for example due to shorter product life cycles and manifold customer requirements cannot be handled anymore. The application of StCM on complex systems is often challenging. Various uncertainties affect this stage as the final design and properties are not clear yet. A lot of other factors such as the quality of the available information, or the skills of the modelers also have to be considered. Thereby, the shape of occurring uncertainty can be manifold and have several features.

This paper presents an approach on the precautionary identification of uncertainties. Therefore, based on a literature review on different types of uncertainty and an approach on uncertainty management from another modeling discipline, we present the Uncertainty Process step Matrix (UPsM). The UPsM identifies and sensitizes for the incorporation of uncertainty into the model. It encourages modelers to recognize the locations of their specific uncertainty and thus, this approach serves as a step towards precautionary uncertainty management.

Keywords: uncertainty, complexity, early design phase, structural complexity management

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1 INTRODUCTION

Complexity increases steadily in engineering design (Clarkson and Eckert 2005, Lindemann *et al.* 2009). This is because of various reasons: Shorter product life cycles, various customer requirements, increasing solution space due to new technical developments, the combination of products and services and other reasons lead to a possibly time-variant high number of elements and relations that have to be considered within an engineering system (Biedermann and Lindemann 2011). For example, augmented product functionalities and growing market diversification lead to increasing variant numbers (Lindemann *et al.* 2009). On the other hand, organizational- and process-complexity may occur and need to be handled. If complexity is not managed successfully, this results in increased time-to-market, costs and wrong decisions with disadvantageous and long-term consequences (Kreimeyer 2009). Complexity in engineering design is closely linked to the fact that engineering design needs to pay attention to an increasing number of aspects. This leads to a growing amount of information about the engineering system that has to be considered. Consequently, techniques for mastering the overwhelming amount of information are important to successfully understand, design and improve complex systems (Eppinger and Browning 2012).

The Structural Complexity Management (StCM) methodology is one approach for dealing with information about complex systems in engineering design (Lindemann *et al.* 2009). The approach bases on modeling a complex system by its underlying structure. The structural model is analyzed in order to identify structural characteristics that indicate potential improvement for the focused systems. We define a model according to Stachowiak (1973) as a representation of an original that reflects a selection of an original's properties and is used in place of the original with respect to some purpose and within a certain time.

Structural models are special types of models that represent the complex system in form of elements and relevant relations between these elements. During the modeling process, information about the complex system (the original) is gathered and represented in a certain modeling language (Kühne 2006). The modeling process and the subsequent analysis of the model involve various stakeholders with specific roles (e.g. experts, modelers) that have to be taken into account (Renger *et al.* 2008). In the modeling process and the model analysis, uncertainty strongly influences the capability of StCM for understanding, designing and improving the complex system (see Figure 1). For example, the choice of data sources, the level of detail, the necessary elements and the appropriate analysis criteria are influenced by uncertainty. The uncertainty in modeling processes can range from ambiguity in defining problems and goals to uncertainty in data and models (Refsgaard *et al.* 2007). In structural complexity modeling, the usefulness of the model for managing complexity decreases with the overall uncertainty about the content of the model as the model may not sufficiently represent the system anymore. Also during the model application, uncertainties concerning the choice of adequate structural characteristics may have an impact on the resulting decisions.

Uncertainty assessment of models is necessary, when structural models are built to support the handling of complex systems. However, in practical application, model uncertainty management is currently only carried out as an end of pipe analysis when the model is already complete (Refsgaard *et al.* 2007). Additionally, it is necessary to carry out uncertainty management as an ongoing activity from the beginning with the problem definition and identification of model objectives and then throughout the modeling process.

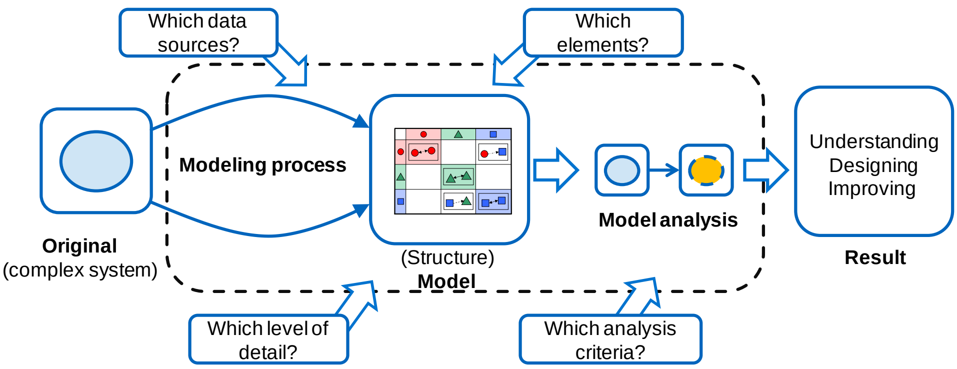

Figure 1. Exemplary uncertainties within Structural Complexity Management

In this paper, we present an approach to support the construction and analysis of structure models. The approach in based on a categorization of uncertainties by their location and their influence on the information generated in the different process steps of the StCM. Thus, this approach identifies and sensitizes for uncertainties that have to be considered for the different steps and serves as a connection to known approaches of uncertainty management. The approach can be used by modelers to improve the quality of structural models and their analysis results. Occurring uncertainties are recognized more efficiently and possibly negative effects can be mitigated effectively. Our main research question can be stated according to the goals of the approach:
How can uncertainties in the StCM methodology be identified and resulting negative consequences be reduced?
The paper is structured as follows: First we provide the necessary background for the approach. Thereby, we give a brief overview on Structural Complexity Management methodology and the state of the art as well as a definition of uncertainty. To tackle the uncertainty effects on the StCM, as a first step, different types of uncertainty are identified within a literature review. We present ordering approaches by the location of uncertainty, the level of uncertainty, as well as by the nature of uncertainty. The different process steps of structural modeling are then identified according to generated information and mapped on the detailed locations of uncertainty. Therefore, we present the Uncertainty Process step Matrix (UPsM), which was filled out by an expert focus group with values of the different locations of uncertainty for each process step. Consequently the use of the UPsM is evaluated by the experiences of other selected experts on StCM by applying the UPsM. Finally, we interpret and discuss the results and conclude with an outlook on future work.

2 STATE OF THE ART

2.1 Structural Complexity Management

Every system that contains at least two parts possesses an underlying structure (Boardman and Sauser 2006). If the underlying structure is known, this allows for conclusions about the system behavior itself and leads to improved understanding. Complex technical products comprise multiple dependencies between their components. This results in difficulties designing a specific component. Information about the internal product dependencies is required to determine the possible consequences resulting from single adaptations. Knowledge about these structural dependencies enables the developers to better manage complexity and therefore, for example, decrease time-to-market. (Lindemann *et al.* 2009)
A common approach to handle complex systems is Structural Complexity Management (StCM) (Lindemann *et al.* 2009). This approach combines the possibilities of the Design Structure Matrices (DSM) (Steward 1981) and the Domain Mapping Matrices (DMM) (Danilovic and Browning 2004). DSM and DMM methodologies are applied for modeling and analyzing system structures in a multitude of different projects in which elements of different domains are focused (for an overview see (Browning 2001). The StCM methodology – as a combination of both approaches – supports the handling of multiple-domain systems. Thereby, domains represent the classification of the elements in groups (Lindemann *et al.* 2009). Examples of domains are people and requirements and single elements represent specific instances of these groups. The StCM methodology provides a five-phase procedure that supports users in system definition, information acquisition, deduction of indirect dependencies, structure analysis, and the application on the product design (see Figure 2).

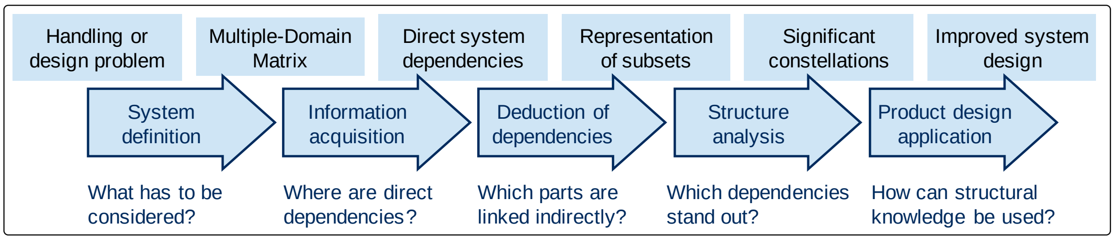

Figure 2. Phases of the StCM methodology (adapted from (Lindemann *et al.* 2009)*)*

For the deduction of indirect dependencies and structure analysis, algorithms for calculating DSMs from DMMs are used. The analyses are computed in the Multiple Domain Matrix (MDM) which

consists of at least two, but theoretically up to an infinite number of domains. The domains (and with it the granularity of the model) are chosen either according to the intended results of the later analysis or according to the existing information sources (Lindemann *et al.* 2009).
Whereas StCM has been created in the context of engineering design of products, it has been enlarged to several other areas of research recently, e.g. process improvement (Kreimeyer 2009), knowledge transfer (Maurer 2011), or security management (Maurer *et al.* 2009). Software support is available for supporting the acquisition, representation and analysis of system structures [http://www.dsmweb.org].

2.2 Uncertainty classifications in modeling

Terms related to uncertainty such as risk, error, and ignorance as well as uncertainty itself are defined differently by different authors; see (Walker et al. 2003) for a review. The different interpretations of the terms represent the different views on the topic of different sciences. In our paper, we regard uncertainty as one main influence on the modeling process and on the subsequent use of models. For the field of modeling Walker et al. (2003) define uncertainty as:
Uncertainty is any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system (original).
There are many different possibilities of characterizing uncertainty depending on different viewpoints.
Walker et al. (2003) introduces the uncertainty matrix as a tool to systematically identify and characterize uncertainties in model-based decision support. The dimensions of uncertainty proposed Walker et al. (2003) are illustrated in Figure 3. The uncertainty matrix suggests that the location of uncertainty, the level of uncertainty, and the nature of the uncertainty define a three dimensional concept of uncertainty. Walker et al. (2003) argue that the model developers and users will become aware of and address all of the important elements of uncertainty, if they identify the level, location and nature of the uncertainty associated with models.
Within this paper we give a brief review of these three common classifications of uncertainty.

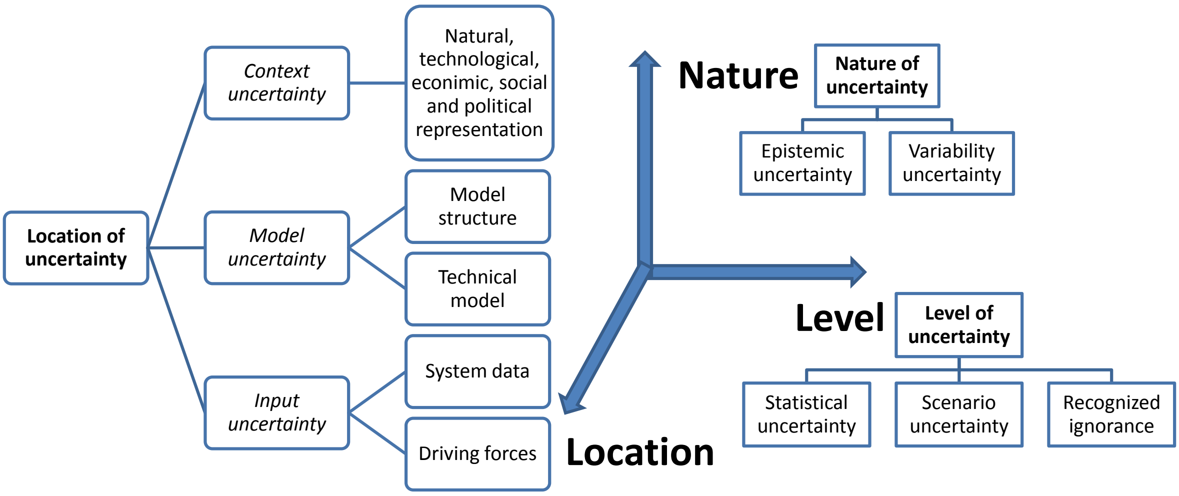

Figure 3. Three-dimensional concept of the uncertainty matrix as proposed by (Walker *et al.* 2003)

Location of uncertainty

After Walker et al. (2003) uncertainty establishes itself at different locations in the model and in the modeling process. **Context uncertainty** comprises the boundaries of the system to be modeled which are crucial for issues addressed within the modeling activity. **Model structure uncertainty** is the uncertainty due to imperfect comprehension of the system or too simplified descriptions of the situation in contrast to reality. **Input uncertainty** refers to the uncertainty driven by the reliability of the accessible system data and also the uncertainty about external driving forces that produce changes within the system model. **Model technical uncertainty** is the uncertainty that arises from the implementation of the model such as software errors or hidden flaws. Walker et al. (2003) also mention *parameter uncertainty* as another location or source of uncertainty. Parameter uncertainty is associated with the methods and data used to calibrate the model parameters. In accordance with Refsgaard et al. (2007), we see parameter uncertainty closely linked to model structure uncertainty and as there are few parameters to be calibrated within the StCM methodology, we consider parameter uncertainty as a part of model structure uncertainty and not as an own location.

Level of uncertainty

Uncertainty can also be ordered by its level (Walker *et al.* 2003, Refsgaard *et al.* 2007). **Statistical uncertainty** can be interpreted as a known degree of unreliability. It is ideally completely described by a probability distribution. **Estimated uncertainty** describes a situation in which a deviation of a characteristic is recognized but its probability distribution is not known or only known partially. An example would be the inherent uncertainty of a scenario of the future. **Unknown uncertainty** is associated with the lack of awareness about the deviation of a characteristic or the lack of awareness that knowledge is imperfect or wrong.

Nature of uncertainty

Walker et al. (2003) further group uncertainty by its nature, which can be categorized into epistemic and stochastic uncertainty. **Epistemic uncertainty is** i.e. the uncertainty due to imperfect knowledge. Epistemic uncertainty can usually be decreased by further knowledge acquisition. **Stochastic uncertainty** is i.e. the uncertainty due to inherent variability. Stochastic uncertainty is inherent for most systems and thus non-reducible. (Refsgaard et al. 2007)

2.3 Uncertainty Management in StCM and research gap

The original uncertainty matrix as introduced by Walker et al. (2003) and the modified uncertainty by Refsgaard et al. (2007) serve as tools to cope with uncertainties with a focus on simulation modeling. But to use their matrices uncertainties already have to be identified. Thus, only subsequent uncertainty management is possible. This approach is not sufficient for the special needs of structural modeling: Often the modelers are not aware at which phase of the StCM methodology, which uncertainties have to be considered in depth. Therefore a method for the precautionary identification of uncertainty within the StCM procedure is needed. Once a specific uncertainty challenge is recognized, the approaches of Walker et al.(2003) and Refsgaard et al. (2007) enable for an engrossed determination of the specific type of uncertainty and their instructions can be followed for uncertainty management. Thus, precautionary uncertainty management would bring additional benefit as it prevents modelers to insert uncertainty into their models instead of subsequent uncertainty assessment.

3 SOLUTION APPROACH

Based on the introduction of the uncertainty matrix by Walker et al. (2003) and its advancements by Refsgaard et al. (2007) we propose to map the locations of uncertainty on the particular process steps of StCM. Therefore, we identified the process steps in the phases of the StCM methodology according to generated information. In each step, the persons involved in the process can then judge whether there exists an uncertainty that influences the generation of the information or not.

This prior step identifies uncertainties and sensitizes modelers for their incorporation, as this is not possible with the classic uncertainty matrices of Walker et al. (2003) and Refsgaard et al. (2007). Consequently, this enables the closer examination of uncertainty in terms of level and nature by the classic uncertainty matrices.

The Uncertainty Process step Matrix (UPsM) presents the mapping of locations of uncertainty on the process steps of StCM. An expert focus group on structural modeling prefilled the matrix in workshops based on their experiences. Thereby the typical values for each location of uncertainty at each process step provide a guideline through the modeling process, especially for less experienced modelers. Throughout the different steps of the modeling process, modelers can use the UPsM to identify the typically most critical locations of uncertainty and thereby the UPsM enables modelers to prevent its incorporation.

3.1 Process steps of the StCM methodology

As a first step the phases of the StCM methodology are broken down into process steps in order to analyze the influence of uncertainty more detailed. We analyzed the StCM methodology according to necessary generation of information in the phases. The following Figure 4 shows the identified main process steps and the therein generated information. Generated information is grouped within one process step if a close relation between the information pieces exists. For example, the generation of information about the elements is closely related to the mapping of elements and domains and was therefore grouped within the process step *Definition of elements*.

Process step	Generated information
Defintion of domains	Domains and attribute of domains (name and description)
Definition of dependencies (direct & indirect)	Dependency Types Mapping of domains and dependency types
Definition of elements	Elements Mapping of elements and domains
Defintion of relations	Mapping of elements and relations (relations between elements) Attributes of relations (e.g. strength)
Computation of indirect dependencies	Indirect dependencies Indirect relations between elements
Structure Analysis (Choice of analysis method & application of the analysis)	Applied analysis criteria and methods
Product design application	Description of tasks for applying the analysis relults

Figure 4. Process steps (taken from (Lindemann *et al.* 2009)*) and therein generated information*

3.2 Classification of uncertainty by its location

Within our approach we use the classification of uncertainty by its location as suggested by Walker et al. (2003), see Figure 5. Walker also provides classifications by the level and nature of uncertainty. Furthermore, Refsgaard et al. (2007) state that the uncertainty matrix is in reality three-dimensional. Thus, the categories location, level and nature are not mutually exclusive. These classifications can be seen as features of uncertainty and therefore each of them specifies a part of the uncertainties' structure.

Uncertainty	Description
System boundary and boundary conditions	Boundary of the system against the environment. Knowledge of all environmental factors that have an influence on the system
Model structure (Conceptual model)	Knowledge about integral parts and interactions of the system
Technical (Implementation)	Projection of integral parts and interactions of the system on the model
Model analysis	Validation of analysis criteria in context of the model purpose
Driving forces	Manipulation (actuate/impair) of the required information
System data	Information the activity is based on

Figure 5. Locations of uncertainty

The classification by the location of uncertainty was chosen as it is necessary to know the location of uncertainty for the detection its level and nature. Furthermore, it is the one easiest to access for modeling practitioners, especially as our goal is to support modelers which may not be familiar to the different classifications of uncertainty.

In adoption of Walker et al. (2003), the different specifications of the location uncertainty were further grouped into the three subclasses: context, model and input, see Figure 3. This enables modelers to decide on the first sight from which subclass their uncertainty is caused. For the model subclass, Walker et al. (2003) and Refsgaard et al. (2007) mention that the uncertainty location can be further specified into structural and technical issues. Within the context of structural modeling we suggest to further include the **Model analysis uncertainty.**

The model analysis uncertainty is the uncertainty due to unknown significance of the analysis results. Thus, if the right problem has been identified and if this problem can be solved by the way the analysis method suggests. This kind of uncertainty separates itself from the model technical and structural uncertainty as these two point to an unknown validity of the model. Model analysis uncertainty is in fact, the uncertainty due to lack of knowledge about the validity of the analysis method applied on the model.
For the input subclass, one has to further identify if the uncertainty is caused from external driving forces that i.e. affect the system data, or if i.e. the quality of the underlying data itself incorporates uncertainty.

3.3 Identification of occurrences of uncertainty locations for each StCM step

For precautionary uncertainty management, the locations of uncertainty have to be mapped on the different process steps of StCM. Figure 6 presents the Uncertainty Process step Matrix (UPsM): With the UPsM it is possible to identify critical features of uncertainty for each process step of the StCM. This proves helpful, as due to the different activities at each step, different locations of uncertainty have to be considered.
The UPsM provides typical values of uncertainty for each step to sensitize inexperienced as well as experienced modelers for the different locations of uncertainty. The values only consider the uncertainty incorporation at the particular process step and cannot be seen as aggregated values that also include the uncertainty from previous steps.
The values were acquired within workshops with an expert focus group on StCM consisting out of 6 systems engineering practitioners and PhD students.
Thereby, the expert focus group discussed each location of uncertainty for each process step separately and the influence of the location of uncertainty on the respective process step of structural modeling was rated on a four-step scale (empty circle for no influence to filled circle for high influence). This scale was chosen as the rating was qualitative because no specific problems were rated and typical challenges within the particular steps were considered. Nevertheless the range of this scale was wide enough to indicate high and low probabilities of uncertainty insertion.

	Process steps of structural modeling						
Locations of uncertainty	Defintion of domains	Definition of dependencies (direct & indirect)	Definition of elements	Defintion of relations	Computation of indirect dependencies	Structure analysis	Product design application
System boundary and boundary conditions	●	◕	◔	◔	○	○	◕
Model structure (Conceptual model)	●	◕	●	●	○	◕	●
Model technical (Implementation)	◕	◕	◕	◕	●	◕	○
Model analysis	◔	◔	○	○	○	●	●
Driving forces	◕	◔	◕	◕	○	◕	●
System data	●	◕	◕	◕	○	◕	●

Figure 6. Prefilled generic Uncertainty Process step Matrix (UPsM)

3.4 Interpretation of perceived uncertainty values

A look on the distribution of the suggested values of the experts shows several trends.
Firstly, an addition of the single uncertainty values for each process step (columns) reveals the highest total uncertainty for the first and at the last process step. For the first step this may be because at the beginning of the modeling process, circumstances are vague. Nevertheless, modeling decisions in this

phase have a high impact on the subsequent modeling steps. For the last process step *product design application*, uncertainty may be high as this is the step where concrete real world decisions are conducted from the model; thus, all previous incorporations of uncertainty result in uncertainty at this step. The absence of model technical uncertainty for the product design application step can be explained by the fact that the technical implementation and analysis of the model are already finished to this point.

For the process step *computation of indirect dependencies* it can be seen that only *model technical uncertainty* plays a role. Indirect dependencies are automatically computed from the already modeled direct dependencies, thereby no “new” information for the model is generated and thus no uncertainty can be incorporated by “new” information, but nevertheless technical errors can occur.

Furthermore it can be noted that the *context uncertainty* decreases throughout the modeling process: The context is formed by economic, political, social and technological circumstances and usually clarified in the early phase of the modeling process. With each process step, the boundaries of the model become more defined. As an example the boundary conditions increase by the definition of domains and dependencies and with defined domains and dependencies it becomes clearer which elements and relations to consider.

Counting the total uncertainty values for each location of uncertainty (row), it can be seen that *model structure uncertainty* is the location that adds the most uncertainty to the overall modeling process. This agrees well with the fact that the model structure is the key point of Structural Complexity Management methodology. Thus, a high degree of certainty about the structure of the underlying real system is crucial for successful structural modeling. Additionally, modelers are often not experts in the field to be modeled, but are chosen because of their knowledge about StCM. Hence, uncertainty may be introduced in the system by interpretations of modelers as they do not understand the real structure of the system: The modeler’s system knowledge may not be sufficient to correctly decide whether or not there is i.e. a relation. Furthermore, uncertainty can be incorporated in the model, because depending on the importance of this decision and the effort to get additional knowledge, it may be more beneficial for the modeler to decide with the current less confidential knowledge (Biedermann 2009). Another possibility would be that the modeler might not even be aware of the insufficiency of his knowledge.

Model analysis uncertainty only plays a major role at the last two process steps. These are the steps where the model is finally analyzed. At the first two process steps there are also other values than zero for model analysis uncertainty as the selection of domains influences the useable tools for the later analysis.

The values of *model technical uncertainty* are mainly constant except for the already mentioned compilation of indirect dependencies. This can be attributed to the fact that technical errors always have to be taken into account. Technical errors may be: software errors such as bugs in the software, typing errors, or design errors in algorithms. Another possibility are technical flaws during modeling, for example because of lacking skills of the modelers that use or create a structural model. Furthermore, random influences such as errors out of tiredness have to be considered. As mentioned, the exception for the last process step may be because no “new” information is incorporated there and the model is also already analyzed, thus the probability of technical errors is very low. One can mention that errors may occur while interpreting the structure analysis results, but we see this still at the structure analysis step and interpret the product design application step strictly only as application of the analysis results.

The values of the *two input uncertainty locations* offer similar trends than the model structure uncertainty. This agrees well with the circumstance that the assessment of the structure of the system has to be based on the available information. Consequently, input uncertainty, referring to the information input, has a direct influence on the model structure uncertainty. Thus, the quality of a model is reliable on the available information. For example, data could be old and no longer valid, or experts may overestimate their knowledge and misinterpret the system to be modeled (Biedermann 2009). Difficult to evaluate are misjudgments on purpose. For example, could an expert misinterpret the system on purpose to make his own field more important, structured or organized. Manipulation of data in general has to be taken into account.

3.5 Initial evaluation of the approach

According to Blessing and Chakrabarti (2009) it can be distinguished between three types of evaluation: support evaluation, application evaluation, success evaluation. Within this paper we assess the potential of the UPsM by the support evaluation. Support evaluation involves verification, that is, checking that the support fulfills the requirements (Blessing and Chakrabarti 2009). In the context of this work the requirements were to sensitize users for the incorporation and identification of uncertainties they have not been aware of before using the approach.

The support for modelers by the UPsM was evaluated on an initial basis by a workshop with selected experts on the StCM methodology. During the evaluation it was remarked that the previously used scale of the UPsM from 0 to 3 should be improved to increase usability. Consequently, it was changed towards the here presented more clear representation with circles. The experts also noted that the UPsM is beneficial as it helps modelers to not forget about a particular uncertainty source at the different process steps. Thus, it is a guideline for a complete consideration of uncertainties and also supports modelers in prioritizing uncertainties. The experts additionally stated that the UPsM is a tool to sensitize modelers for so far unconsidered uncertainties such as the high model technical uncertainty for the process step *computation of indirect dependencies*. In this particular case, an expert noticed an uncertainty source he has not been actively conscious of before. Furthermore, it was remarked that best practice approaches to mitigate identified uncertainties would be a desirable addition.

4 CONCLUSION AND OUTLOOK

This paper presents an approach for precautionary uncertainty identification within Structural Complexity Management (StCM). Thereby as a first step, a classification of different uncertainty locations is suggested to explicit the various sources and occurrences of uncertainty. This classification is then mapped on the different process steps of the StCM methodology to build the Uncertainty Process step Matrix (UPsM). Derived by workshops with an expert focus group on StCM, the filled version of the UPsM provides typical values of uncertainty for each location of uncertainty at each of the process steps. With the filled UPsM inexperienced as well as experienced modelers can be sensitized for typical uncertainty locations for each specific process step of StCM. By sensitizing modelers for uncertainty incorporations throughout the StCM methodology, the UPsM serves as a tool for precautionary uncertainty identification. The usability and usefulness of the UPsM has been initially evaluated with selected experts on the StCM methodology.

The UPsM enables modelers to identify and be aware of specific uncertainty challenges at the StCM methodology. Thereby, it facilitates precautionary uncertainty management by using the approaches of Walker et al. (2003) and Refsgaard et al. (2007) to determine the specific type of uncertainty in depth. This brings additional benefit as it prevents modelers to incorporate uncertainty into their models instead of subsequent uncertainty management as intended by the original uncertainty matrices. Furthermore, modelers can fill the UPsM themselves for their particular modeling task to become aware of and address all the important uncertainty types for their specific uncertainty. Nevertheless the usefulness of this particular application still has to be proven.

As intended in the present research agenda and in accordance with the results of the initial evaluation, future work includes the investigation and development of mitigating opportunities for uncertainty incorporation. The focus of the support for handling uncertainty in StCM will be put according to the identified most critical locations in the single process steps.

ACKNOWLEDGMENTS

We thank the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG) for funding this project as part of the collaborative research centre ‘Sonderforschungsbereich 768 – Managing cycles in innovation processes – Integrated development of product-service-systems based on technical products’.

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