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INTEGRATING STRUCTURE AND UNCERTAINTY MODELING USING MULTIPLE-DOMAIN-MATRICES

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1. Introduction

The development of innovative products is a fundamental key factor for business success on global markets. However, new product development is accompanied by uncertainties that endanger the compliance with budget, schedule and quality. Different types of uncertainties occur in new product development that either refer to the product or to the development process and finally lead to risks. In order to reduce risks, it is necessary to prevent uncertainties as early as possible. The key to effective and efficient risk management is therefore facing risks proactively [Smith 2002]. This exactly means that risks are identified and counteracted before they affect the project in a serious way. In literature several phases of proactive risk management are distinguished that generally can be outlined as "risk identification", "risk analysis" and "risk response" (see fig. 1). According to the described phases, the procedure of proactive risk management starts with the identification of uncertainties. After that, the identified uncertainties are evaluated, aiming to determine the risks. Hereby risk evaluation has two facets: the determination of the probability of failing and the analysis of the consequences or impacts of failing. Finally, counteractions for risk reduction are generated.

For each of the three phases, methodical support is available. Methods, like Failure Mode and Effects Analysis (FMEA) for risk identification, Monte Carlo Simulation for risk evaluation and prototyping and testing for risk response are established and well known techniques. At the same time the demand for risk management increases, an effective application of risk management becomes difficult. Products nowadays are characterized by a high level of complexity and interdisciplinarity what in consequence leads to complex development processes. Due to this situation, uncertainties are often not restricted to the point of their occurrence. Instead, the appearance of one uncertainty can cause new uncertainties that are explainable by the existence of strong relations between the product and process elements. We can exemplarily consider the development process of a brake unit in the automobile industry. Changing the size of the brake later on during the design process will automatically require changes of the brake booster, because both system elements and their associated process steps are directly related to each other. Thus, an uncertainty regarding the brake size leads to new uncertainties, concerning the brake booster. The necessity to change the brake size can in turn be the result of uncertain requirements.

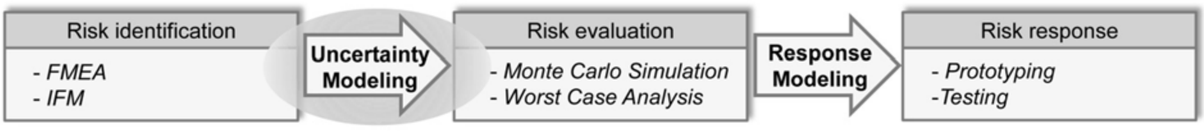

Figure 1. Phases and methodical support in proactive risk management

The example points out that uncertainty analysis is associated with, both, the product and process structure. To understand the influence and importance of uncertainties, it is therefore reasonable to integrate uncertainty analysis and structure analysis. It is furthermore expedient, to support the analysis by providing an integrated structure and uncertainty model. Models are capable to represent reality in a simplified manner by focussing on the information of interest for a specific problem. In the described context of new product development, an integrated structure and uncertainty model is useful to predict the propagation of uncertainties. Hereby a model can support decision making by simulating different scenarios. It can also be established as an adequate way of documentation and thus support communication by enabling a common comprehension about a situation. As depicted in fig. 1, uncertainty modeling therefore serves as the link between the phases of risk identification and risk evaluation. This publication introduces the concept for an integrated uncertainty and structure modeling approach. The approach is first described in a general manner. Afterwards an example application is presented.

2. Basics and literature review

In this chapter relevant basics and state-of-the-art in research are presented. These address the topics of uncertainty and uncertainty analysis as well as structure and complexity modeling.

2.1 Uncertainty and uncertainty modeling

In general, uncertainties can be defined as any condition that is characterized as not definite, known or reliable. Thus, uncertainties are the result of imperfect knowledge. In new product development, different types of uncertainties occur during the development process. Missing knowledge about the customer´s needs, results in uncertain requirements. In conceptual and detailed design, uncertainties arise that regard the chosen concept or technology. Furthermore, new product development requires new development processes that can also be uncertain. This publication distinguishes between the classes of "requirement uncertainties", "system uncertainties" and "process uncertainties that lead to "quality uncertainties", "cost uncertainties" and "schedule uncertainties". Fig. 2 depicts the relations between the different types of uncertainties that overall are allocated to the product and its development process.

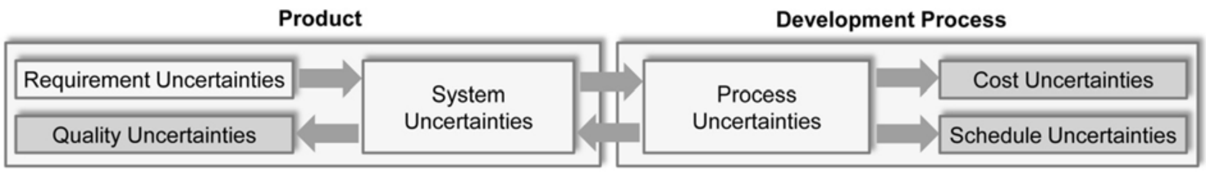

Figure 2. Interrelations between different types of uncertainties

Uncertainty models are used in design processes to support decision making by predicting the effects of uncertainties. Thus, they provide the basic for risk evaluation. Most of the approaches described in literature consider uncertainty as a problem that can be modeled using probability theory [Du 2004]. In a probabilistic model parameters are treated as fuzzy, causing a statistical distribution of their outputs. Uncertainties are quantified by the use of error boundaries that are either based on subjective expectations on the outputs or objective uncertainty measurements [Martin 2005]. Uncertainties can be measured by observations of reality or are the result of past experience. Most of the uncertainty models described in literature either concentrate on process uncertainties or product uncertainties. In the context of the analysis of process uncertainty, the probability of deviations within budget and time are determined. In comparison, the analysis of product uncertainty refers to discrepancies of the product properties that are e.g. caused by deviations in the production process. A comprehensive approach for uncertainty analysis is given by the Uncertainty Mode and Effects Analysis (UMEA) [Engelhardt 2011]. The UMEA describes a methodical approach to identify uncertainties and their causes during the entire life cycle of the product. To the best of our knowledge, an approach for integrated structure and uncertainty modeling does not exist yet.

Especially in the early phases of product development, quantitative uncertainty modeling is often too complex or not even possible to realize. In this publication uncertainty propagation is therefore exclusively considered on a qualitative level.

2.2 Product and process structure modeling

The term "product structure" describes the relationship between the elements of a product. In general, product elements are classified hierarchically by their level of detail (system, subsystem, part) or by their level of abstraction (component, working-principle, function). In the broadest sense, requirements can also be understood as product elements, representing an image of the product from a customer´s point of view. Comparable to the product structure, the process structure contains information about relations among process elements. Product structure and process structure are directly related, because process relations represent necessary information flows that arise from interdependencies between product elements. The literature provides numerous research that either deals with product structure modeling [Langdon 1995] or process structure modeling [Eppinger 1994]. Comparatively few approaches are known that integrate both types of models [Blomeyer 2003]. In this publication the integrated modeling of product and process structure is denoted "structure modeling".

2.3 Complexity modeling

The complexity of technical systems or processes depends on the quantity of elements and their relations. Complex systems or processes are often challenging to represent clearly. Methods like workflow diagrams e.g. do not adequately simplify complex processes and thus are often not suitable to give an overview about the network at once. A useful technique for modeling and analysing complex structures is given by the Design Structure Matrix (DSM) [Browning 2001]. DSMs are square matrices with corresponding rows and columns. The diagonal cells describe the elements, while off-diagonal cells indicate their interdependencies. Directional as well as non-directional relations can be differentiated in a DSM if both halfs of the matrix are used. A geometrical relation between two components e.g. contains a non-directional relation, while information flows between process elements are often directed. An instrument to relate two different domains is the Domain Mapping Matrix (DMM) [Danilovic 2007]. However, DMMs are limited to combinations of two domains only. For the relation of more than two domains, Multiple-Domain Matrices (MDMs) were developed that comprise DSMs and DMMs [Maurer 2007]. For each domain, a DSM is aligned along the diagonal of the MDM that contains the domain specific elements and their inter-domain relations[1]. Intra-domain relations[2] are expressed in DMMs that are arranged above and below the diagonal. The choice of domain combinations is not restricted to a defined set of domains and thus can be adapted to a specific problem.

3. Integrating structure and uncertainty modeling

The presented approach for the described problem integrates two partial models for structure and uncertainty analysis that are combined in a MDM based model. The structure model (see fig. 3) contains the three domains "requirements", "system elements" and "process elements" whose elements and inter-domain relations are represented within DSMs on the diagonal of the MDM. While the DSMs, representing requirements and system elements, exclusively contain non-directional relations and thus are symmetric, the process DSM also comprehends directional relations to display information flows. Intra-domain relations between requirements and system elements as well as system elements and process elements are modeled within particular DMMs. Here the requirements and system elements mapping DMM on the upper half indicates the influence of requirements on system elements. The one on the lower half displays the fulfillment of requirements by system elements. In contrast the upper DMM, connecting system elements and process elements, provides information which system elements have to be considered to execute a process step, while the DMM on the lower half illustrates, which system elements are affected by results of a process step.

[1] Inter-domain relations are denoted as interdependencies between elements of the same domain
[2] Intra-domain relations occur between elements of differen domains

Initial generation of the structure model preferably starts with modeling the product information. Therefore requirements and system elements including their inter-domain relations are modeled first in steps 1 and 2, followed by a description of the associated intra-domain relations in steps 3 and 4. For process modeling, the process DSM gets filled with process elements and their relations in step 5. The order of process elements can be optimized using common methods for DSM based process optimization [McCulley 1996], which are not subject of this paper. Finally, intra-domain relations between system elements and process elements are marked in the accordant DMMs in steps 6 and 7.

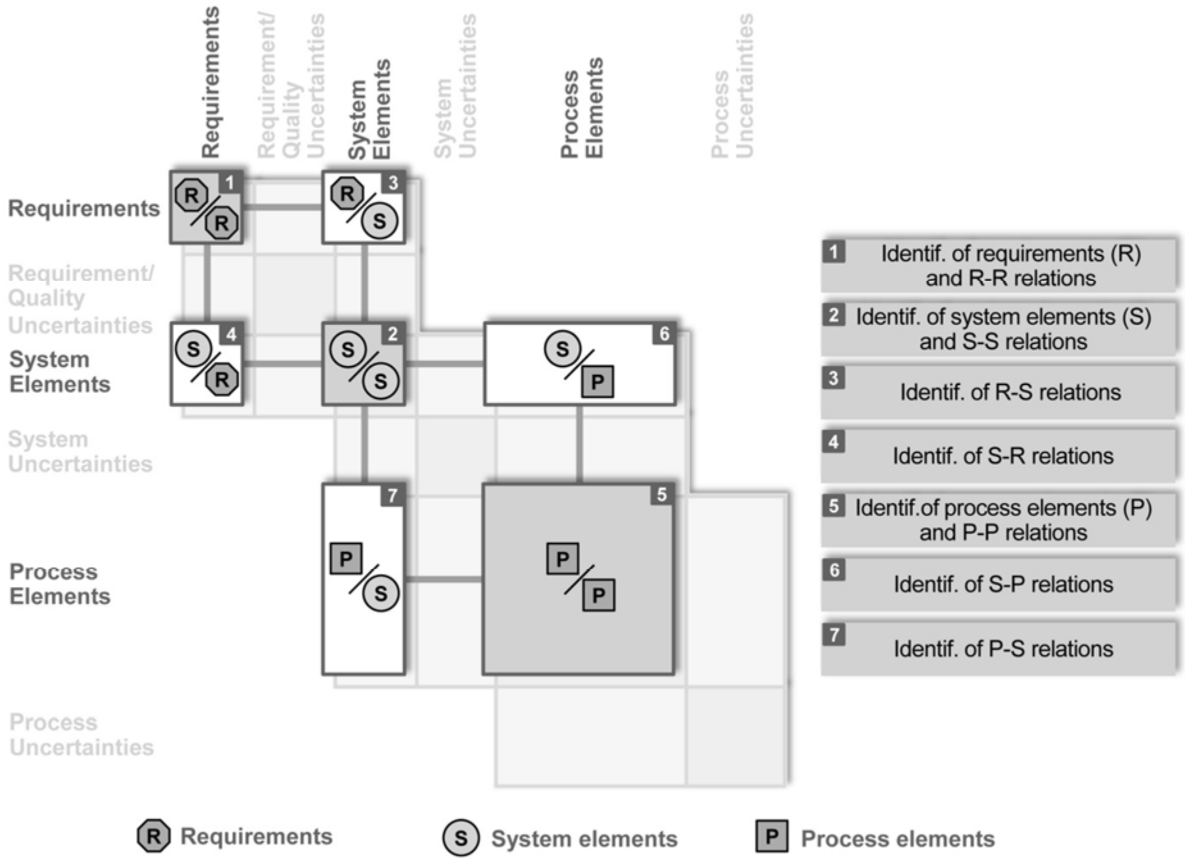

Figure 3. Structure model as part of the integrated structure and uncertainty model

The uncertainty model (see fig. 4) contains the domains "requirement/quality uncertainties", "system uncertainties" and "process uncertainties" that are arranged in additional DSMs between the sub-matrices of the structure model. Requirement uncertainties and quality uncertainties are expressed in the identical matrix to clarify that both types refer to the requirement domain of the structure model. Cost and schedule uncertainties are not explicitly depicted in the uncertainty model, because they are implicitly contained within the process uncertainties. DMMs below and beside each uncertainty domain represent the elements of the structure domains that are affected by the uncertainties. For example a change of requirements (step 11) leads to a requirement uncertainty (step 12) that in consequence affects system elements (step 13). Vice versa, system changes (step 24) evoke a quality uncertainty (step 25) that finally effects quality aspects (step 26).

The particular property of the presented approach is supporting a follow-up for uncertainties of different types. Hence, no explicit starting point for an uncertainty analysis exists. Two exemplary ways are presented in fig. 4. The first one, already mentioned before, starts with an identification of requirement changes (step 11) and results in process uncertainties (step 18). The second one is initiated by a process uncertainty (step 19) that results in system uncertainties (step 22) and finally in quality uncertainties (step 25) that concern requirements (listed in step 26). Beside the describable intra-domain dispersion of uncertainties, the consequences of uncertainties within the same domain can be envisioned as well. For example, a system uncertainty could entail another system uncertainty, if a relation between affected system elements exists. Such relations can in turn be origin for new inter- and intra-domain propagation of uncertainties.

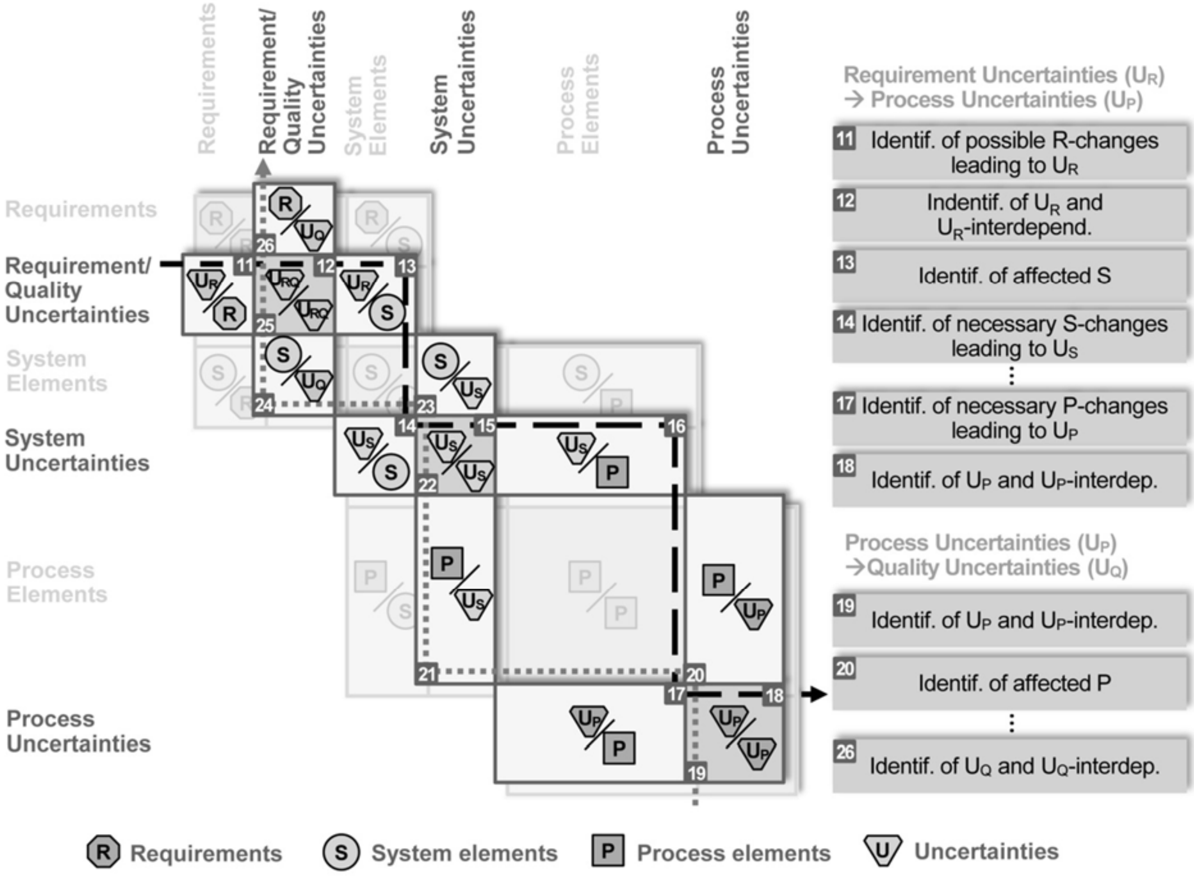

Figure 4. Uncertainty model as part of the integrated structure and uncertainty model

4. Example

To further elaborate the proposed concept, the approach is applied to a fictive design project of a pencil sharpener. A top down proceeding is chosen to simplify the example.

The pencil sharpener pictured in fig. 5 consists of four system elements called "pen fixture (S1)", "cutter (S2)", "basket (S3)" and "body (S4)". The four assembly groups are not further disassembled for the example because the presented approach supports an application with different levels of detail.

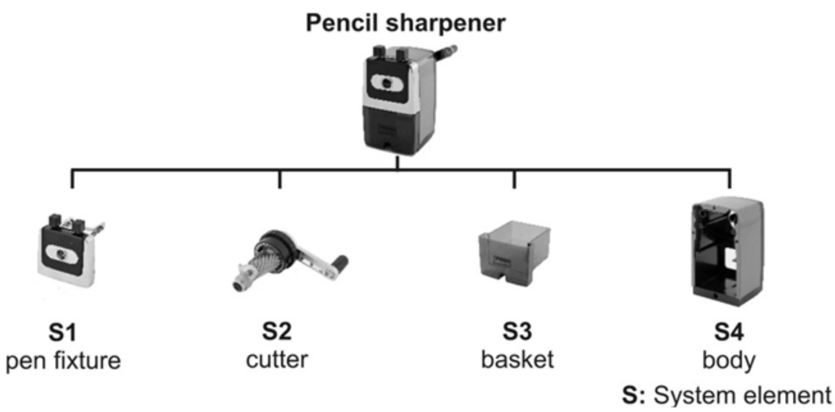

Figure 5. System composition of a pencil sharpener

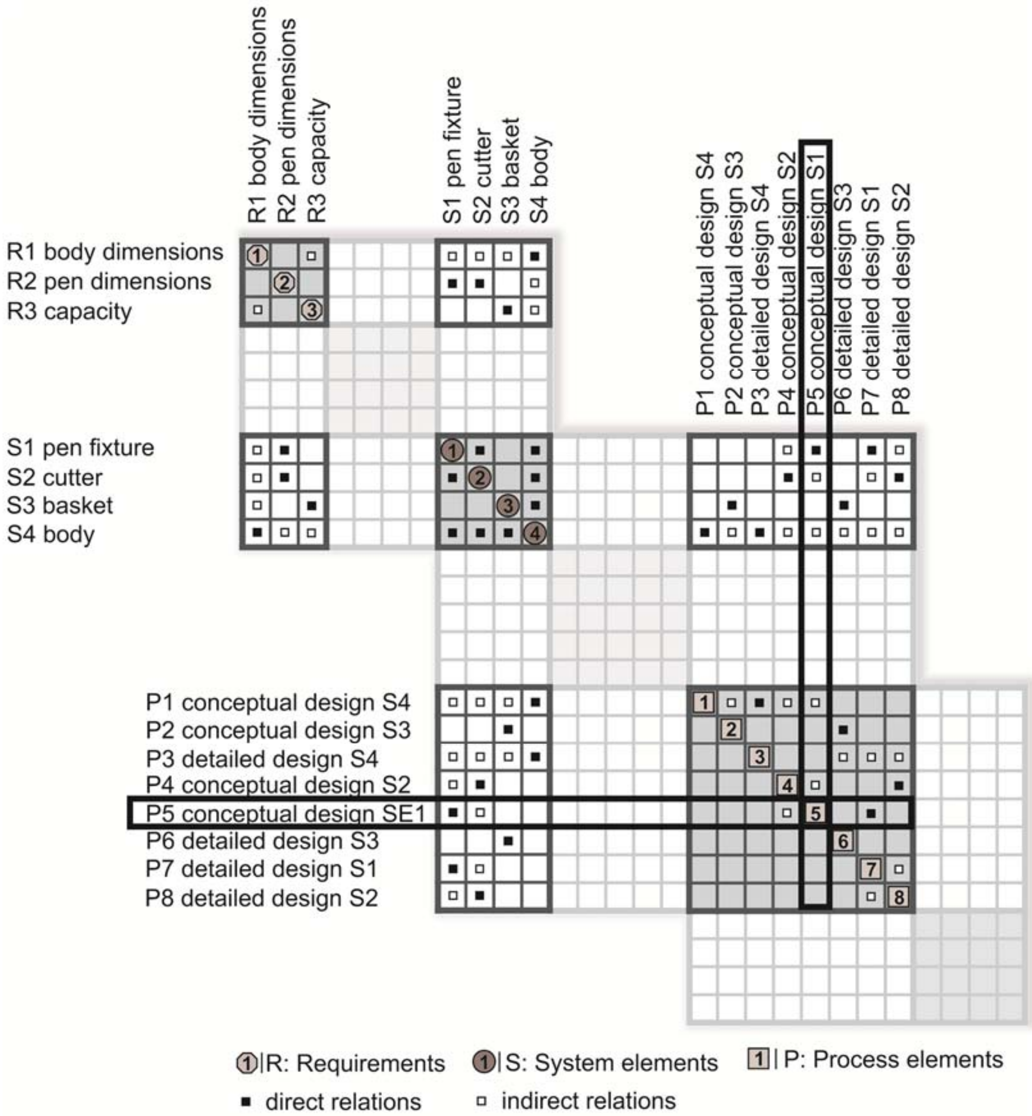

Figure 6. Structure model of the pencil sharpener and its development process

The generation of the structure model (see fig. 6) takes place in the described manner, starting with the declaration of requirements and system elements as well as the identification of the inter- and intra-domain relations. Interdependencies are differentiated into direct and indirect relations[3], marked by filled and unfilled squares respectively. As displayed in fig. 6, three requirements are identified that regard to the body dimensions, the pen dimensions and the filling capacity of the pencil sharpener. An indirect relation between the body dimensions (R1) and the capacity (R3) is identified, resulting from a direct relation between the basket (S3) and the body (S4). This cognition is not surprising, because a change of body dimensions directly affects the basket size and vice versa.

Within the process DSM, the marked direct relations express that process elements belong to the same system element. Furthermore, marks located on the upper half of the diagonal indicate feedforward relations while the ones located on the lower half must be interpreted as feedback relations. Having a closer look on the highlighted process element P5 (conceptual design of pen fixture (S1)), the process relations in the column imply the reception of input information for P5 provided by process elements P1 (conceptual design of body (S4)) and P4 (conceptual design of cutter (S2)). In contrast the relations marked in the row describe the flow of output information delivered as input information for process

[3] Indirect relations occur as result of the combination of different relations. Relations between system elements are direct interdependencies by definition.

elements P4 (conceptual design of cutter (S2)) and P7 (detailed design of pen fixture (S1)). Therefore, the entries in the upper system and process mapping DMM illustrate that for execution of process element P5 the cutter (S2) as well as the body (S4) have to be considered beside the pen fixture (S1). The marks in the DMM below indicate that the pen fixture (S1) and the cutter (S2) are affected by results of the considered process step.

With rising complexity, it is sometimes impossible to gather complete information in the model. To complete such information it is helpful to control the consistency between direct and indirect relations continuously. Useful methods to support information acquisition are presented in [Maurer 2007]. It is important to understand structure modeling as an iterative process that has to be adapted to the progress of the development project.

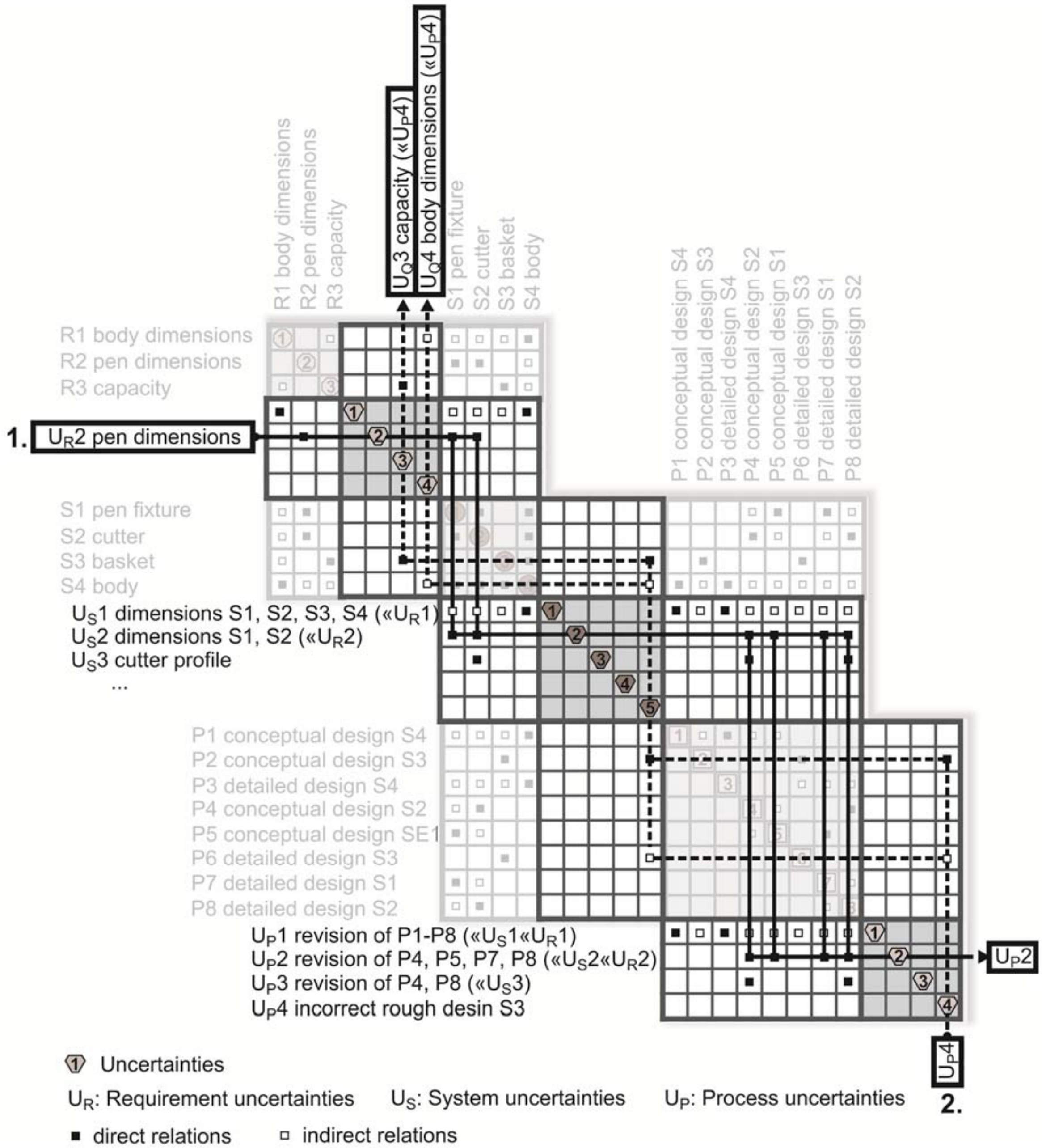

Figure 7. Uncertainty model of the pencil sharpener and its development process

To clarify the process for uncertainty modelling, two different uncertainties, serving as source for complex uncertainty propagation, are highlighted in the uncertainty model (see fig. 7). The first one

belongs to the type of requirement uncertainties and regards the requested pen dimensions that are characterized to be uncertain in the beginning of the project (U_R2). A direct relation of U_R2 to the system elements pen fixture (S1) and cutter (S2) is identified, because both system elements are geometrically coupled and are directly affected by the pen geometry. The relations to the pen fixture (S1) and the cutter (S2) necessitate changes of the mentioned system elements that are subsumed as system uncertainty U_S2 in the model. As displayed in the structure model, the required system changes occur within the process elements P4, P5, P7 and P8 that in consequence deserve a revision. The process changes are summarized as process uncertainty U_P2. The second uncertainty is characterized as a process uncertainty (U_P4), concerning possible mistakes in the conceptual design process of the basket (S3). As displayed, beside a direct relation to the rough design process step P2 an indirect relation to the detailed design step P6 exists. From a system´s point of view, the basket (S3) as well as the body (S4) receive system uncertainty that finally endangers the fulfilment of the capacity requirements and the requested body dimensions and therefore leads to quality uncertainties.
As displayed in fig. 7, changes of two different system elements are subsumed within system uncertainty U_S2. Principially both changes can also be split up into two independent system uncertainties, as done for the quality uncertainties U_Q3 and U_Q4. A decision for the type of embodiment should be made in dependency of the user´s experience.
Fig. 8 visualizes the propagation of uncertainties in another manner. The chosen type of representation is denoted "uncertainty tree" in this publication. Each block of the uncertainty tree describes one uncertainty, identifiable by its initials in the upper field. A detailed describtion of the uncertainty is given in the field below. The fields on the left and on the right indicate the elements that are affected. The uncertainty tree enables a representation of relations between uncertainties in a hierarchical manner. It can be automatically generated out of the MDM if computer assistance is used. The uncertainty tree can help to extract the consequences of uncertainties from the holistic model.

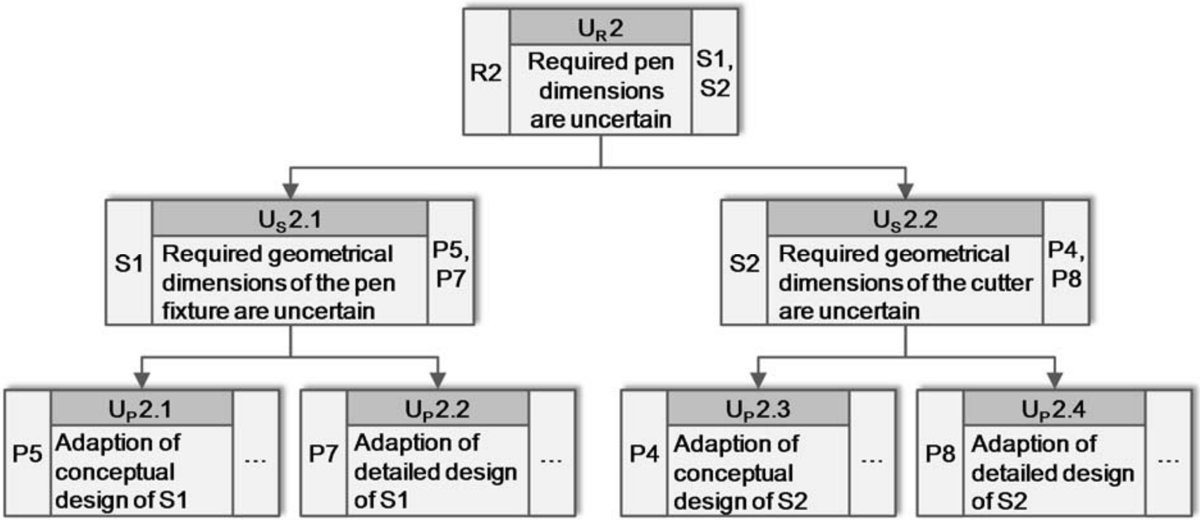

Figure 8. Extract of an uncertainty tree for the pencil sharpener

5. Discussion

The research presented in this publication provides three important results that are discussed below:

1. Integrating structure and uncertainty modeling can support the identification of uncertainties and their propagation in a significant manner. Even the simple example of the pencil sharpener demonstrates that complex product and process structures are characterized by complex uncertainty propagation. An integrated model enables the identification of hidden uncertainties that are the result of structure interdependencies.
2. The results also show that MDMs are suitable to deal with complexity in the described context of risk management. MDMs are capable to give an overview about uncertainty propagation in

the project by representing it in a simplified but holistic manner. A more detailed or specific view on uncertainties can be achieved by extracting uncertainty trees from the holistic model.

3. The presented concept for an integrated modeling approach provides adequate documentation of uncertainty propagation. It establishes a common comprehension of uncertainties within the involved actors. This is of particular importance for the phase of risk response, because the propagation of uncertainties necessitates a common risk response. Hereby, the integration of structure and uncertainty model again is helpful to identify the affected actors.

The results presented in this publication raise new questions that could not be answered completely so far. Up to now, the outlined approach is very theory driven. Further research has to be provided considering the applicability of the approach to real development projects. Overall, several matrices have to be filled, resulting in an increasing effort for model generation. Nevertheless, the authors believe in the suitability of the approach because of the fact that DSM and MDM can be applied on several levels of detail. In order to reduce the effort for model generation, the level of detail can be adapted to the level of criticality. For noncritical parts of the system a low detailed model can be chosen while critical parts are analyzed on a high level of detail. The authors already used this technique in the presented example of the pencil sharpener, where the system was analyzed on the level of assembly groups instead of components. Grouping noncritical elements within the model can therefore help to focus attention on the elements of particular interest.

However, the results also indicate that further research is needed to complete the outlined approach. The topics for continuative research are listed below:

I) In terms of the structure model, a key aspect needing further attention is the broader specification of system elements within the model. In the given example application, a high level of concretion is chosen, implicating that all components of the system are already known. However, our experience teaches us that new product development usually occurs on different levels of abstraction. Innovative thinking often requires sudden switching between these levels. It is therefore of particular interest to distinguish system elements of different level of abstraction and detail within the model.

II) Furthermore, the discussed concept only allows the representation of interdependencies by binary entries. More detailed analyses are enabled if the MDM contains additional information about the elements and their relations, such as the types of relations and their strength.

III) Above all, computer assistance is necessary to enfold the entire potentials of the approach. It is not only necessary to automatically generate uncertainty trees as mentioned before but also to reduce the effort of dynamic changes during the project.

6. Summary

This publication proposes the concept for an integrated structure and uncertainty model based on MDM. The model integrates the domains requirements, system elements and process elements as well as associated requirement and quality uncertainties, system uncertainties and process uncertainties. Hereby detailed analysis of uncertainties and their influence on other domains are expected to be enabled that are prerequisite for a proactive risk management. The presented example application for the fictive design project of a pencil sharpener suggests that integrating structure and uncertainty modeling is a useful enhancement for proactive risk management applicable in the phases of risk identification and risk evaluation. However, the outlined approach is just a starting point for a holistic structure and uncertainty model that has to be pursued in further research to enhance the proposed approach.

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