INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

DEVELOPMENT OF A METHODICAL APPROACH TO HANDLE UNCERTAINTY DURING THE PROCESS OF PRODUCT MODELLING

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Keywords: product modelling, uncertainty, assumptions, product lifecycle

1. Introduction

Product models represent a product at a defined abstract level. They contain only information relevant to a certain task and are the results of the process of product modelling [VDI 2221]. They are used in decision support for certain tasks or problems during the product development process, for example, to define or verify product properties where product behaviour is influenced.
Product models are based on assumptions, concepts or schemata made by the designer [Dremont et al. 2011]. In the early stages of the product development process, most of the information about the product being developed is unknown or vague, creating a gap between available levels of information and required levels of information.
This may lead to the product model representing known or unknown information irrelevant to the task (Figure 1). Furthermore, the product model may contain only some of the information required for a given task, where the information can be known or unknown. It is also possible that known, relevant information is not adequately represented in the product model.

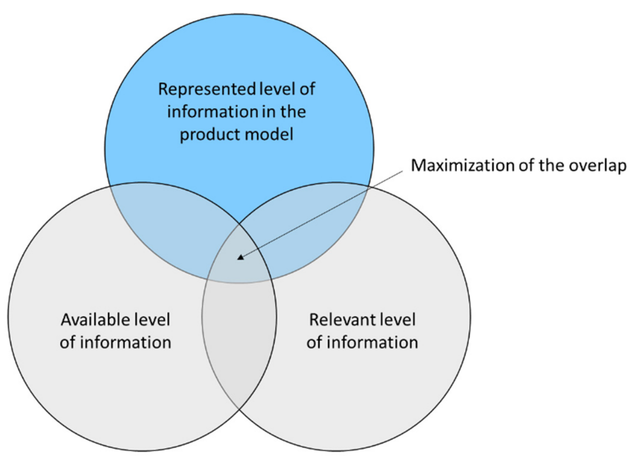

Figure 1. Available, relevant and represented levels of information in a product model

Designers have to make assumptions, often with a lack of information, when creating and representing unknown information in a product model. This may lead to uncertainty if relevant information is neglected or is insufficient; the product model can be incomplete or unsuitable for the given task.

Because product models are used for decision support during the product development process, variations between realized and planned product behaviour may occur. There is a need to support the designer to handle uncertainty during the process of product modelling.
The research focus is on what kind of support should be provided to the designer to evaluate and improve assumptions. Therefore, this paper provides an approach that can be used during the process of product modelling. With its help, the overlap between the available level, the relevant level and the represented level of information in a product model can be maximized.

2. Definitional basics

This section sets some definition basics that are necessary to understand the approach.

2.1 Uncertainty

The approach was developed by Collaborative Research Centre SFB 805, which investigates uncertainty in load-carrying structures in mechanical engineering to inform its handling [Hanselka and Platz 2010]. Uncertainty occurs in processes [Eifler et al. 2011] and is a situation that results from completely or partially missing information, understanding or knowledge [DIN 31000]. There is a correlation between the level of information and uncertainty, where a high level of information is related to a low level of uncertainty and vice versa. Uncertainty can be described as being where division into uncertainty in data and uncertainty in models is used. For this approach, only uncertainty in models is relevant. It can be divided into the following three categories, where increasing levels of available, trusted relations in a model is apparent:

- Unknown relations
- Incomplete or disregarded relations
- Assumed relations that can be verified and validated

2.2 Process

A process has an initial state and a final state, and describes the transformation between the two states within a system boundary [Heidemann 2001], [Kloberdanz 2009]. To execute the process, an appliance that provides a working factor to fulfil the transformation is necessary [Heidemann 2001], [Kloberdanz 2009]. In the context of this approach, the process of product modelling describes a transformation from a given task or problem to a product model and the designer is the appliance that provides the working factor to fulfil it (Figure 2). Therefore, the designer uses the level of information that is available.

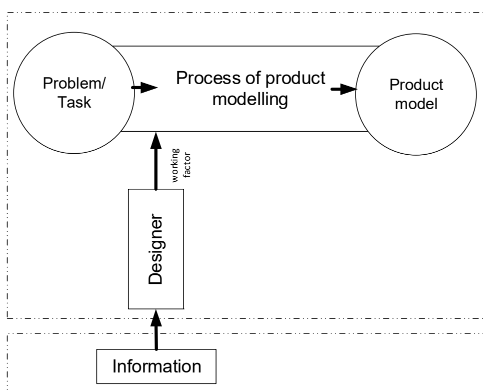

Figure 2. Process of product modelling

3. Systemizing the process of product modelling

To understand the kinds of assumptions that a designer has to make, the process of product modelling has to be systemised.

As mentioned previously, the process of product modelling describes the transformation of a given problem or task to a product model. During this process, the designer sets the characteristics pragmatism, representation and shortening [Stachowiak 1973], [Würtenberger et al. 2015]:

- Pragmatism describes for whom the model is developed. The point of time in which the model is used is set and its use is specified.
- Representation describes the way in which the original attributes are represented by the model. Attributes in this context are properties that describe what individuals perceive. This characteristic can be compared to the understanding of attribution in mathematics.
- Shortening - Only the attributes of the original product or model that are relevant to the designer are investigated in the model. The selection of attributes made here can be partly pragmatic, so shortening can be made random to a certain purpose.

These characteristics describe how the designer has to make assumptions by asking the questions "for whom/what", "in which way" and "what is relevant".

The process of product modelling contains sub-processes that describe continuous individualization until the creation of the product model is finished (Figure 3).

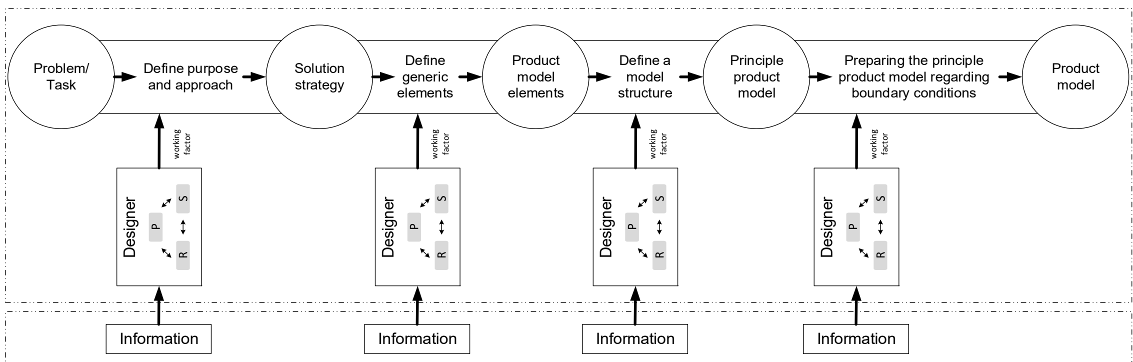

Figure 3. Process of product modelling

The first sub-process describes transformation from a given problem or task to a solution strategy. The designer has to think about aspects that definitely have to be considered to solve the problem or task. The characteristic pragmatism dominates this sub-process.

Generic elements then have to be defined to fulfil the solution strategy. The designer has to think about the language of the product model. For example, a mathematical, a graphical or a textual model is about the level of abstraction at which the product model should be created. Functional, effect, working principle or embodiment levels are conceivable here. This sub-process is dominated by the characteristics pragmatism and representation.

The next sub-process focuses on the definition of the model's structure. The designer has to think about existing model representations that suit the assumptions made so far. From this, a model room is visible and the principle product model can be deduced. The characteristic representation dominates here.

The principle product model then has to be prepared for boundary conditions. During this sub-process, the designer focuses on shortening, making assumptions according to which information is relevant to the principle product model and how they can be shortened. The process of product modelling is then finished and the designer can use the product model to support decision-making. The sub-processes give the designer an indication of which assumptions have to be made.

During each sub-process, one characteristic dominates. However, assumptions based on the dominant characteristic always include aspects of the other ones. For example, if the designer makes a pragmatic assumption, the level of information is automatically shortened, which limits the possibilities of representation. All assumptions are dependent on the whole process of product modelling, for example, a pragmatic assumption made during the first sub-process limits the possibility of shortening the level of information by preparing the principle model for boundary conditions.

Uncertainty in the context of product modelling needs to be discussed. As mentioned above, uncertainty in models can be described by relations that are included in the model. By integrating assumptions that have to be made, a cause and effect relationship is visible. An unsuitable or incorrect assumption is the cause of a missing relation in a model. Based on this, uncertainty in product modelling can be defined [Würtenberger et al. 2015]:

- Product modelling uncertainty occurs when it is not clear that all relevant influences and dependencies have been considered during the creation of a product model. Product modelling uncertainty is made up of pragmatism uncertainty, representation uncertainty and shortening uncertainty.

By systemizing the process of product modelling and understanding uncertainty in this context, the research question can be discussed by developing an approach to evaluate and improve assumptions.

4. Approach for evaluating and improving assumptions during product modelling

As mentioned in the introduction, variations between realized and planned product behaviour may occur when unsuitable or incorrect assumptions are made during the process of product modelling. Because of this dependency, the relation between the process chains of product development and product lifecycle is investigated and used as the basis for developing an approach to improve assumptions.

4.1 The process chains of product development and product lifecycle

The process chain product development in Figure 4 represents the development process (as per VDI 2221) and contains the working steps 'clarifying the task', 'conceptual design', 'embodiment design' and 'detail design'.

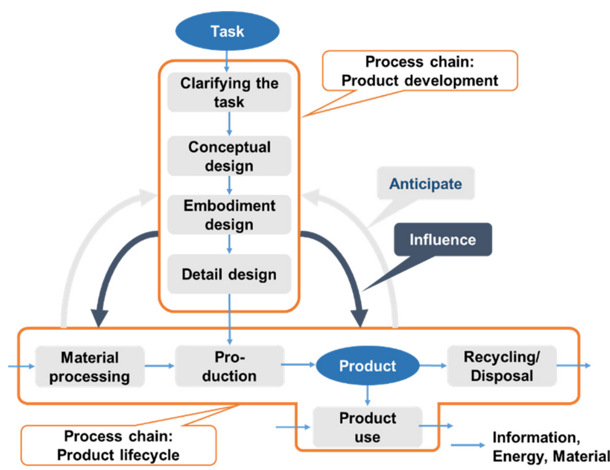

Figure 4. Process chains: product development and product lifecycle [Birkhofer et al. 2012]

The process chain product lifecycle includes all stages in the lifecycle of a product, beginning with material processing, production of the product, product use and recycling. The connection between these two chains takes place during the production of the product.

The model also contains the principle of Life-Cycle Thinking: The designer has to think about the product's entire lifecycle during development of a product and has to anticipate which information is relevant. With this help, the designer can influence the product lifecycle.

The principle of Life-Cycle Thinking, especially the anticipation of relevant information, is used in the approach to evaluate and improve assumptions made during the process of product modelling.

Information anticipation has to be carried out methodically to comprehensively support the designer. The approach aims to give the designer recommendations for thinking and acting during the whole process of product modelling in response to anticipation of relevant information and its use.

4.2 The UMEA methodology

To anticipate relevant information from the lifecycle, an existing methodology is used as the starting point. The methodology is called Uncertainty Mode and Effects Analysis (UMEA) [Engelhardt et al.

2011]. It is based on the risk management process in business economics. The UMEA focuses on uncertainty in data, especially in product and process properties.

The UMEA methodology consists of 4 working steps (Figure 5). First, with the help of an environmental and goal analysis, requirements and evaluation criteria concerning the product to be developed are defined for a certain task. With this help, relevant parts of the product lifecycle are set during the second step. All relevant parts are investigated to identify potential risks for uncertainty. The third step determines the effects of the potential risk on relevant product or process properties. Finally, the identified effects are evaluated with the help of requirements and evaluation criteria from the first step, and decisions are made on whether and in which way they are considered during the product development process.

For every step of the UMEA methods and models exist that can be used for support. The choice of model and method used depends on the underlying task [Engelhardt et al. 2011]. For a detailed description of the allocated models and methods see [Engelhardt 2012].

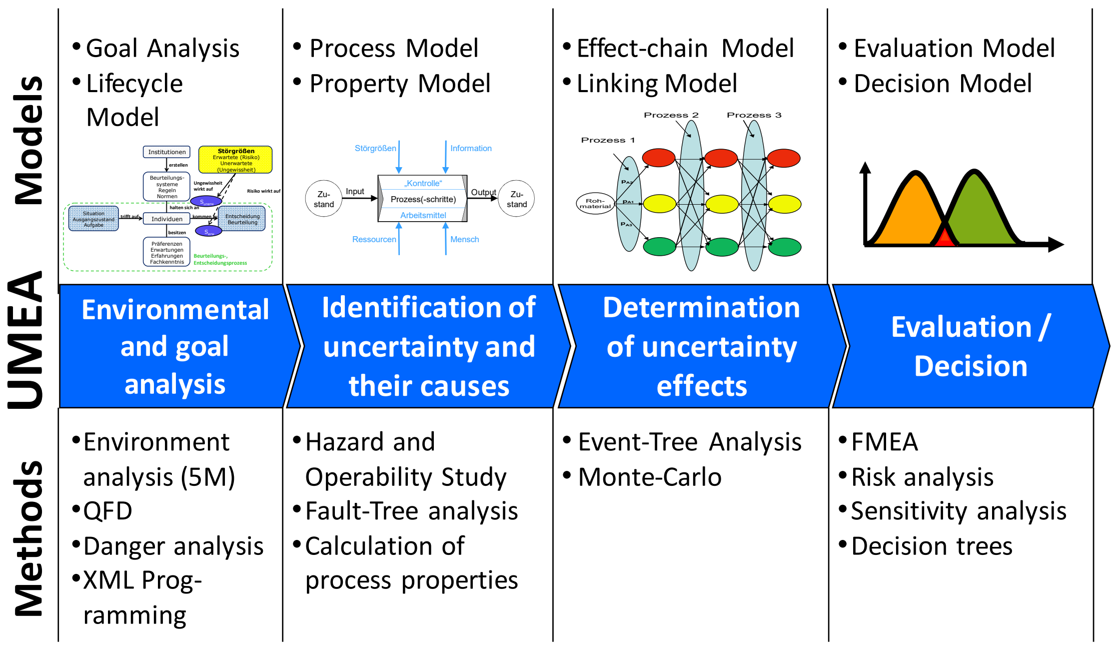

Figure 5. The UMEA Methodology [Engelhardt et al. 2011]

4.3 Approach to evaluating assumptions, based on the UMEA Methodology

The UMEA Methodology, currently used to investigate uncertainty in data, is adapted to become a model-oriented UMEA to analyse uncertainty during the process of product modelling. The aim is to generate a reference value out of the lifecycle in order to evaluate the assumptions which are made during the process of product modelling. If there's a gap between the reference value and the assumption, it is an indicator for uncertainty.

Therefore, the working steps of the UMEA are split into two groups (Figure 6).

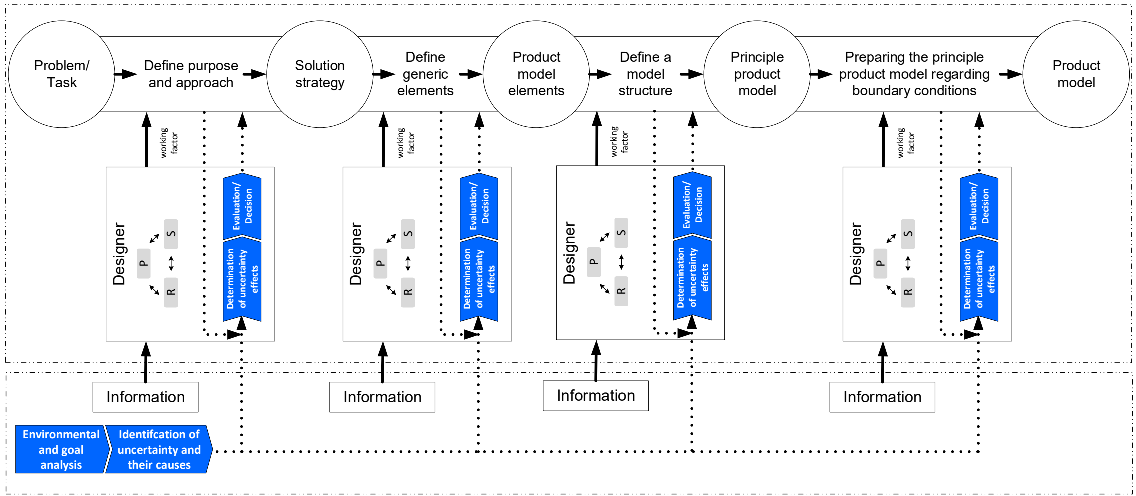

Figure 6. Model-oriented adaption of the UMEA Methodology

Before the process of product modelling starts, the first two working steps are made. During the environmental and goal analysis, a system boundary is defined for a certain problem or task. Which aspects are essential to solve the problem or task, such as which processes of the lifecycle may influence these aspects, is discussed.

During the next working step, all relevant processes of the lifecycle are analysed for the occurrence of influencing factors. With the help of that, reference values can be generated.

The results of the first two working steps are used to evaluate assumptions during each of the sub-processes of product modelling. During the working step 'determination of uncertainty effects', the essential aspects of the problem or task are considered, such as the identified influencing factors of the relevant processes. Here, the comparison between the assumptions and the reference values takes place and a statement according to uncertainty is made.

Depending on the identified uncertainty, during the last working step the necessity of improving assumptions is made. Furthermore, decisions have to be made on how the improvement should take place.

For each of the working steps of the model-oriented UMEA, different models and methods can be used to fulfil it. The next sections provide examples of which of them are possible.

4.3.1 Models and methods for the first model-oriented UMEA step

A model to analyse the environment and goal can be used to discuss and define essential aspects to solve a problem or task (Figure 7). The model focuses on the designer and shows two influencing areas. The designer is influenced by personal preferences, expectations, experiences and knowledge, as well as by existing evaluation systems, rules and standards [Engelhardt et al. 2011]. In this case, they could be design principles, such as known analytical processes of different disciplines in the field of mechanical process engineering. This model can be supported by method questionnaires and checklists to analyse the influenced areas.

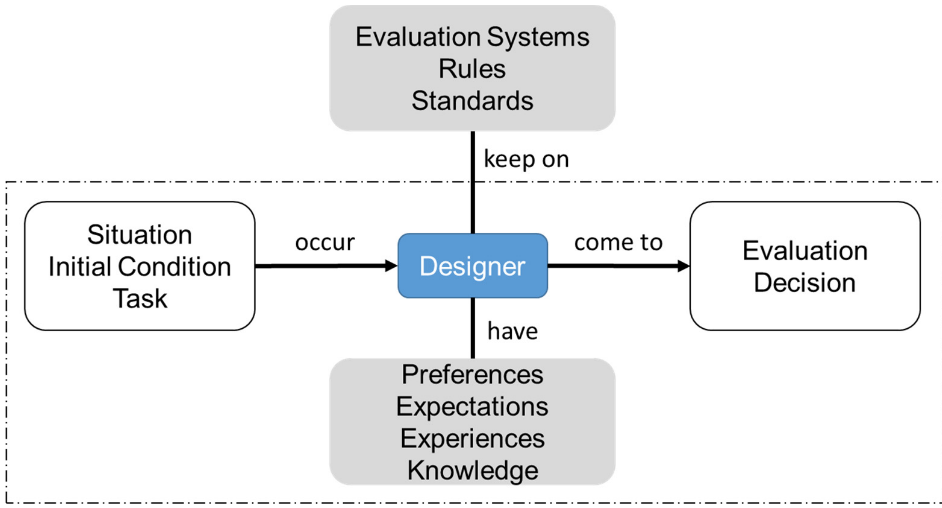

Figure 7. Model to analyse the environment and goal, based on [Engelhardt et al. 2011]

To identify relevant processes in the product lifecycle, the idea of Quality Function Deployment (QFD) can be used [Akao 1990]. The identified aspects of the problem or task are seen as designer requirements and the known processes of the product lifecycle as the corresponding dimension. By evaluating the correlation between them, relevant processes can be identified and prioritised.

4.3.2 Models and methods for the second model-oriented UMEA step

The identification of influencing factors of the relevant, prioritised processes can be carried out using a process model that has been developed in SFB 805 (Figure 8).

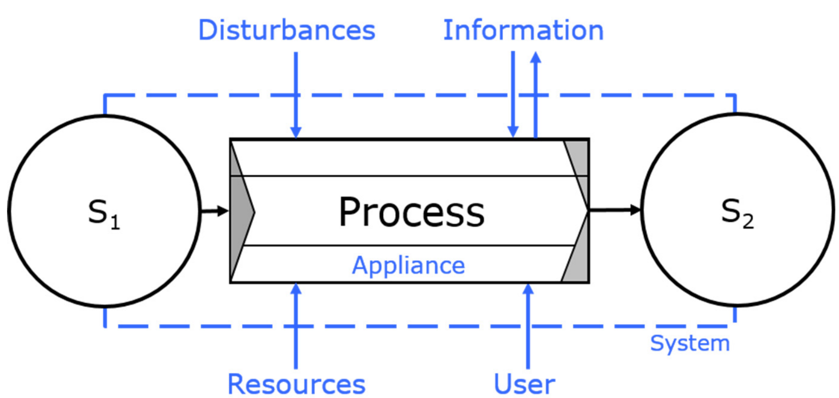

Figure 8. SFB 805 Process Model [Eifler et al. 2011]

The model describes the transformation of state S1 to state S2 within a system boundary (Section 2.2). To fulfil the transformation, an appliance that provides the working factor is necessary. For example, if a bending process is regarded during the production of a product, a bending machine is the appliance. The process is affected by the influencing factors disturbances, information, resources and the user.
Disturbances result from downstream and upstream processes that are outside the system boundary, such as from environmental influences like air humidity or temperature. An example of information could be fabrication information, guidelines or instructions. Resources describe what the appliance requires to fulfil the process, for example, operation and auxiliary materials like energy or coolant. Examples of user influences are dexterity, qualification and experience.
To define influencing factors, various methods can be used, for example, Failure Mode and Effect Analysis (FMEA), Hazard and Operability analysis (HAZOP), or a cause and effect analysis [Engelhardt 2011].

4.3.3 Models and methods for the third model-oriented UMEA step

All identified essential aspects from the first step and the influencing factors from the relevant lifecycle processes are analysed according to whether they are considered within the assumptions and whether the consideration is sufficient. The results of each sub-process are confronted with the information and a sensitivity matrix is set.

During the first sub-process of product modelling, only the essential aspects are regarded (Figure 9). The sensitivity to be evaluated focuses on the question of whether and to what extent the essential aspects are considered in the solution strategy. Here, high sensitivity stands for comprehensive consideration and vice versa.

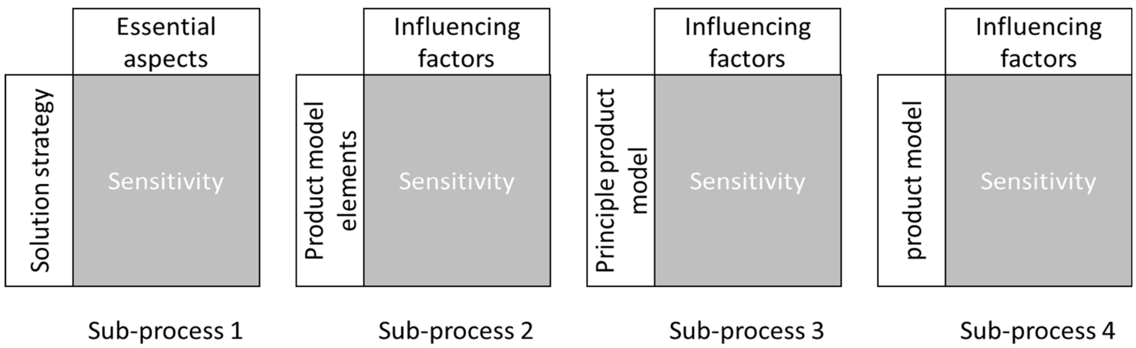

Figure 9. Sensitivity matrices during the process of product modelling

During the second and third sub-processes, only the influencing factors are regarded. Sensitivity evaluates whether these factors can be represented in principle with the help of the defined generic elements and the model structure.

During the last process of product modelling, the issue is whether relevant factors are considered sufficiently by preparing the principle product model for boundary conditions, where a high sensitivity also stands for comprehensive consideration.

To support the sensitivity matrices, the same methods mentioned in Section 4.3.2 can be used.

4.3.4 Models and methods for the fourth model-oriented UMEA step

All essential aspects and influencing factors with low or no sensitivity have to be evaluated for whether they should be integrated into the process of product modelling. Therefore, a risk portfolio can be used (Figure 10).

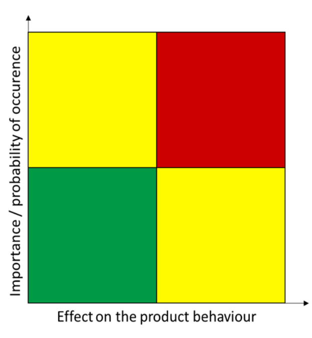

Figure 10. Risk portfolio, based on [Hennings 1996]

Here, the importance of and the effect on product behaviour for each essential aspect, such as the probability of occurrence and the effect on product behaviour of each influencing factor, is evaluated. With this help, prioritization is possible. For all aspects and influencing factors with a high importance or high probability of occurrence, such as big effects on product behaviour, decisions have to be made on which way they should be integrated into the process of product modelling. It is possible to add

additional generic elements or to change them. The model representation chosen or shortening during the last sub-process can be changed.
To support the last UMEA step, the methods Hazard and Operability analysis (HAZOP) or reliability analysis, such as a decision tree or benefit analysis, can be used [Engelhardt et al. 2011].

5. Example

The approach is applied in part using the SFB 805 demonstrator, where only a tetrahedron is investigated. The task is to make a statement on how the tetrahedron behaves if it is loaded with force F. Therefore, a product model is created that contains several assumptions (Figure 11).

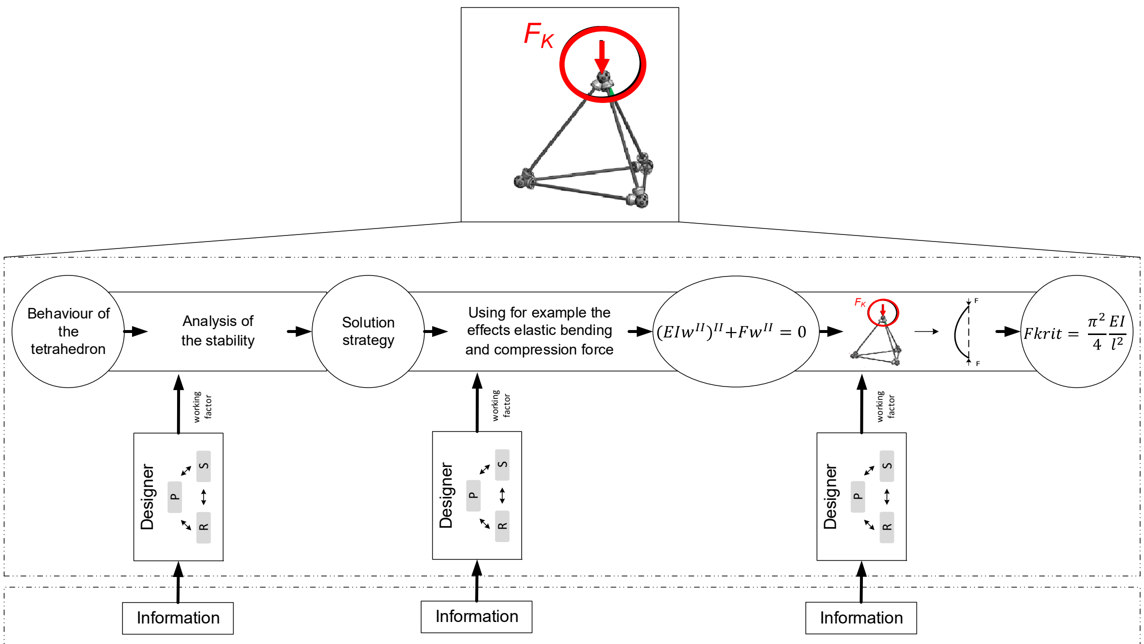

Figure 11. The process of product modelling using a tetrahedron [Würtenberger et al. 2015]

The solution strategy focuses on the analysis of the stability of the tetrahedron. By regarding the effects elastic bending and compression force, the theory of buckling by Euler is set, which is the principle product model here. With this help, the tetrahedron is represented in the product model by using the second case of Euler's buckling load and the product model to analyse the behaviour.
By using the model-oriented UMEA during the process of product modelling, a few points have to be discussed.
For example, during the first UMEA step, the question arises as to why the strength of the bars is not investigated here. The designer has to think about whether to integrate it into the solution strategy. In this case, integration is associated with minimum effort, because the buckling theory also provides information about the deformation of a bar and so only the last sub-process has to be adapted according to the new solution strategy.
During the second UMEA step, there are tensions inside the tetrahedron after the assembly process is finished. The question arises of whether it is possible to integrate the information into the chosen representation beam theory or if it is better to change it into a finite element model. If the designer decides to still use the beam theory, the question during the last sub-process of product modelling is whether the second case of Euler's buckling load is still useful or a change into the first case represents the identified factor better in the product model.

6. Conclusion and outlook

This paper systemizes the process of product modelling to assist understanding of the context in which designers have to make assumptions. Assumptions are characterised by pragmatism, representation and shortening; each of them dominating different sub-processes of product modelling. At the beginning, pragmatic assumptions are the main focus; in the middle, representation; and at the end, shortening assumptions dominate.

To evaluate and improve assumptions, the UMEA Methodology was extended to become model-oriented by focussing on the domination of the assumption types. The approach showed when and in which way the UMEA steps have to be used during the process of product modelling.

In further work, the approach has to be applied to other examples to evaluate it. Allocation of models and methods to the UMEA steps has to be verified and extended.

Acknowledgement

Thank you to the Deutsche Forschungsgemeinschaft (DFG) for funding this project in Collaborative Research Centre SFB 805.

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