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

MODELING SYSTEMS OF OBJECTIVES IN ENGINEERING DESIGN PRACTICE

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ABSTRACT
Objectives are central elements of product development processes. The multitude of objectives forms a system of objectives, which is characterized by a high complexity and dynamic. In engineering design practice, modeling systems of objectives is a challenging task the designers are confronted with.
The research presented in this paper focuses on modeling systems of objectives from a designer's perspective which means that user-friendliness and acceptance of the approach is a central aspect. Based on a literature review, we deduce a lean methodology for modeling systems of objectives and realize an implementation of the approach within an intuitive mind-mapping software-tool.
The results of an application in engineering design practice imply that the approach is user-friendly and mainly accepted by designers in practice; the performance however has to be further improved.

Keywords: system of objectives, requirements, complexity, design practice

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1 INTRODUCTION

Objectives are central elements of product development processes. The multitude of objectives forms a system of objectives, which is characterized by a high complexity, especially in mechatronic development processes requiring several disciplines and designers (cf. Albers et al., 2012). Considering all objectives and interdependencies and the need of depicting the system of objectives to make it available to all members of a development team is a challenge in design practice the designers are confronted with. In addition, the dynamical behavior of objectives and whole system of objectives within the development process increase the complexity beyond the diversity of elements and their relations – change and iterations are relevant factors.

The research presented in this paper focuses on modeling systems of objectives from a designer's perspective which means that acceptance of the approach is one main aspect. Badke-Schaub et al. (2011) identified three main categories of deficits of past and today's design methodology and emphasizes the non-user-friendliness and the missing performance of many design methods. Therefore, our approach for modeling systems of objectives is based on the well-known and intuitive concept of mind mapping representation to satisfy the user-friendliness. We analyze how systems of objectives behave in product development and how they can be modeled against the background of a convenient benefit-cost-ratio. We deduce a lean methodology that shall enable the designers to depict the objectives and their relations in order to support a purposeful product development process. In order to ensure the performance of the approach, we applied it in engineering design practice.

2 OBJECTIVES IN ENGINEERING DESIGN PRACTICE

2.1 Systems of Objectives

In the early stage of product development the designers define an initial system of objectives on the basis of their knowledge and additional information. Sources can be for example problems with the current product in market, wishes from customers or input from market analysis.

Especially in early phases of development projects objectives can only be defined vague and uncertainty is dominating. Customers for example tend to define a requirement list as a first approach, which mostly is incomplete, requirements are missing or other requirements are implied (cf. Grabowski et al., 2002). During the development process information and knowledge is gained, based on development activities and resulting objects, which is needed to concretize the objectives (Albers et al., 2011). Vague objectives result in a high number of possible outcomes and unknown problems which can cause high unexpected effort – time and money – in the further development process. These vague objectives are concretized in two ways. The initially defined objectives can either be refined or redefined (also described as refinement and rework (Wynn et al., 2007)), which depends on positive or negative evaluation. A positive evaluation means the correctness of objectives which then can be defined more in detail. A negative evaluation in contrast indicates wrong objectives and thus the need of changing these elements (Albers et al., 2012). Change in the system of objectives is not the exception but rather the rule. Almefelt et al. (2006) identified several factors for changes:

- knowledge gained through the development work (e.g. through testing),
- requirements found to be conflicting,
- technical difficulties to meet a high specification,
- opportunities for function-sharing and synergies,
- unexpected demands for cost savings,
- new legal requirements, and
- unexpected competitor situations and customer preferences (changed market requirements).

Considering these factors it is obvious that iterations cannot be avoided in the course of the development process. There are always unknown variables in the solution - uncertainty and change are characteristics of the process which has to be involved in design process methodologies and organizational thinking (Darlington and Culley, 2002). Iterations cannot be prevented and have to be considered; they are valuable and essential to gain insights and knowledge (Meboldt et al., 2012). On these grounds Darlington and Culley (2002) concluded, that "*...it is no longer possible to treat the specification as a fixed prescriptive document, it must become an open medium, capable of transmitting the functional and performance requirements and necessary technical adjustments.*"

2.2 Modeling of Objectives

The system of objectives has to be explicated in a certain way, that every member of the development team works and acts with the same understanding or rather same intention. Therefore, a model of the very complex system of objectives has to be explicated. According to Stachowiak (1973) models are characterized by three attributes:

- Representation: Models are always modeling something. They are representations or descriptions of natural or artificial originals, which themselves can be models again.
- Reduction: In general, models do not capture all attributes of the represented original, but only those seeming relevant for the creators or users of the model.
- Pragmatism: There is no direct assignment of models to their originals. The term of a model has to be put into context in a pragmatic way. Models are for someone human or artificial; they fulfill their function for a certain time and were made for a certain purpose.

High effort was made in the past, to explicate objectives and to handle the upcoming complexity. Thereby, the attributes 'reduction' and 'pragmatism' have to be considered carefully when modeling system of objectives. 'Reduction' addresses the question, which information in form of objectives and relation should be modeled and which not. 'Pragmatism' on the other hand addresses the question, how the information should be modeled.

Relating to the aspect 'pragmatism', different authors distinguish different characteristics of objectives. For Hansen and Andreasen (2007) a core element in systems theory is the distinction between structural characteristics and behavioral properties. They divide specification statements in characteristics, which design the system's structure, and properties, which describe the behavior and thereby how it reacts to input and how human beings perceive it. Stechert and Franke (2009) describe vague goals on the top of a relationship model and targets that are more concrete and satisfy the goals. The targets in turn are satisfied by the systems requirements. Additionally Stechert and Franke point out integrating constraints (as quantifiable relations) which allow further descriptions of the relations between different requirements. Finally there are blocks symbolizing the modules of the product which satisfy the according requirements. It is a qualitative statement about the connection between elements of the system structure and the requirements. Chakrabarti (2003) divides requirements into solution-neutral and solution-specific requirements. The original requirements at the beginning of a development project are solution-neutral. While progressing in the development process the designers apply the original requirements by making them more solution-specific (refining cf. to Albers et al., 2012). Depending on the pragmatism according to Stachowiak (1973) each of these characteristics of objectives may occur in product development and each characteristic may be important.

The aspect 'Reduction' is highly connected to an adequate respectively accepted benefit-cost-ratio. In order to support the designers in handling the objectives different strategies were developed in the past, which can be subsumed under the heading 'requirement management'. Large specification documents are used in industry to collect as many objectives as possible and huge software-tools like Rational DOORS are offered to handle the complexity. Both, the demand for a maximum amount of explicit information and the use of powerful but complex software to depict the information often tend to result in negatory users. It's no wonder that despite these special software-tools, the most common tool for handling objectives in industry is Microsoft Office (Hood et al., 2007). Therewith specification documents were created which in turn build the base for further development work. These textual documents are helpful for documenting the initial system of objectives, for example in a table view. This is a feasible procedure to depict the initial system of objective - however, two crucial problems occur in general. Firstly, there is no useful possibility to depict the relations between objectives. Secondly, the effort to keep this document valid and up-to-date rises tremendously while the development process progresses and changes as well as iterations occur. Thus, in further process the text document becomes often outdated as revealed relations and made decision were not depicted. In this way the text document does not represent the actual system of objectives and for this reason it is mostly useless.

In summary, it is still difficult for designers in practice to model the system of objectives, especially when the development process proceeds and refinement, change and iterations occur. Designers in practice can choose between very complex, non-user-friendly, non-intuitive and too simple, too reductive software in order to model the system of objectives. They are supported methodologically in choosing the right pragmatism according to Stachowiak but barely in choosing the right reduction.

3 HANDLING OBJECTIVES IN ENGINEERING DESIGN PRACTICE

For handling complex systems of objectives in engineering design practice an approach is needed which combines user-friendliness and adequate performance in order to achieve the designer's acceptance. Additionally, a lean methodology is required that helps to support the designer to answer the questions of suitable pragmatism and adequate reduction. In the following section we outline the main concepts of the approach which form the basis for an implementation in a mind-mapping software-tool.

3.1 Aspects of Systems Engineering

One part of the definition of the INCOSE Systems Engineering Handbook (Haskins et al., 2011) describes systems engineering as a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect.

Applying this definition on handling system of objectives, wholeness could be interpreted in such a way, that all objectives including all interdependencies should be explicitly depicted. This is in conflict to Stachowiak's attribute 'reduction'. Wholeness can never be achieved in a model and therefore the designers have to focus on a system of interest which has to be defined (cf. to Albers and Lohmeyer, 2012). Albers and Lohmeyer (2012) describe continuousness as a second core element of systems engineering. Relating to systems of objectives continuousness allows depicting all kind of objectives with the same methodology and within the same model. Furthermore, continuousness ensures the rational of decisions and resulting objectives respectively relations. Wholeness and continuousness are essential conditions for applicability which in turn is a necessary precondition for an effective and efficient application of the approach.

3.2 Pragmatism – How to model objectives

If the different characteristics of objectives are kept in mind (cf. section 2.2), the question comes up, if there has to be a difference in depicting e.g. solution-neutral and solution-specific objectives (cf. to Chakrabarti, 2003) or structural characteristics and behavioral properties (cf. Hansen and Andreasen, 2007). As described above, the system of objectives matures by defining, refining or redefining single objectives or relations – starting with objectives defined by the customer, solution-neutral and finally solution-specific objectives. Since new objectives usually do not appear from nowhere but are causally determined, it should always be possible to identify a super-objective that gives a rational explanation of its origin. When an added objective matures, i.e. knowledge and certainty rises, the development of new sub-objectives is expected. The changeover from solution-neutral to solution-specific objectives is often more or less seamless. Mostly it depends on the chosen system of interest whether an (super-)objective is already defining a certain solution or not (cf. figure 1). Therefore, it seems suitable to depict the structural characteristics, the solution-neutral as well as the solution-specific objectives in the same way – sub-objectives relate to their super-objective and form a causal relation. Behavioral aspects such as use-cases must be modeled separately – the resulting objectives however can and should be depicted and also related to the corresponding use-case-model.

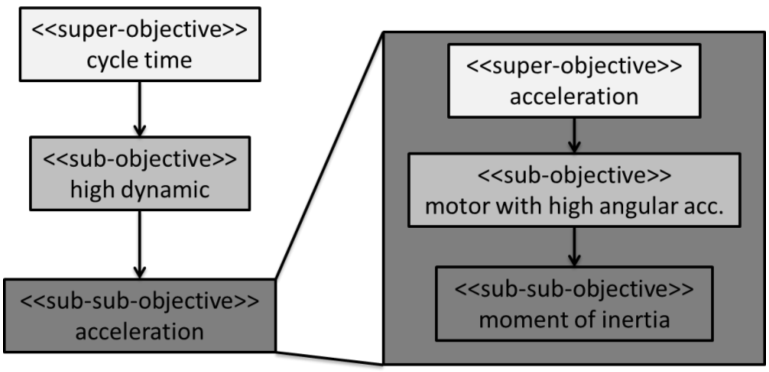

Figure 1. Super- and sub-objectives depending on the system of interest

3.3 Reduction – Which objectives to model

At the first sight it seems counterproductive not to depict every single information that could possibly sharp the system of objectives and therewith the product solution. But there are two crucial arguments, designers in practice should not and do not depict every objective. First, explicating and documenting information requires time which is precious in product development. It is always a trade-off between a) saving time by not depicting the objective and trusting in the knowledge of the involved designers and b) depicting really important objectives in order to avoid misunderstanding and unnecessary iterations. Secondly, depicting too much (irrelevant) information can cause information overflow where the relevant and important core of the information is blurred or fragmented. Albers et al. (2011) propose four dimensions of objectives in order to improve the designer's understanding of single objectives and whole systems of objectives:

- *"The **degree of maturity** describes the completeness regarding the understanding and realization of an element of the system of objectives."*
- *"The **degree of rigidity** indicates the willingness to hold on to an element of the system of objectives. In consequence, it is an indicator for the trustworthiness or rather the changeability of an objective."*
- *"**Leverage** indicates the potential to define/change elements of the system of objectives regarding ability and/or authorization."*
- *"**Impact** is the (anticipated) consequences of an event or decision in terms of necessarily resulting (change) effort/cost/time for the respective system of objectives and/or objects."*

Analyzing a single objective in terms of the four proposed dimensions can help to decide, whether the objective is worth being documented or not. Drawing a portfolio with the axes 'leverage' and 'impact' and the scale 'low' and 'high' for example results in four quadrants that indicate the importance of an objective (trivial, unimportant, important, crucial) and thereby the priority of documentation. Additionally, the dimensions of objectives can be used to easily add incomplete but explicit extra information to single documented objectives in order to avoid time-consuming and/or inefficient modeling effort.

3.4 Design Rationale

It is important to explicate and document objectives since they steer and regulate the product development process (cf. Albers et al. 2012) – they are case-specific knowledge (Klein, 1998). Therefore, it is just as important to preserve the objectives' rational in order to understand, reproduce or reinterpret the decision which is important, e.g. when boundary conditions change, or new knowledge is available. In practice, a significant part of the design knowledge, including design rational, exists only implicit. Wallace et al. (2005) comment: *"When individuals move to another part of the organization, leave or retire, they take their knowledge with them and, in many cases, this knowledge is lost forever."* This is a problem which can cost a lot of effort because of necessary rework. To prevent rework in a current process, the decisions which were made during the development process have to be traceable. This can be done by including the rationale of decisions into the system of objectives.

3.5 Change and Iterations

Change and iterations are ubiquitous in today's product development affecting especially the system of objectives (cf. section 2.1). They are a result of wrong assumptions and/or wrong decisions and therefore always require an adjustment of the system of objectives. In engineering design practice, unforeseen major iterations usually lead to pressure of time resulting in several escalation strategies with the overall objective to save the market launch date (cf. Meboldt et al. 2012). One can imagine that in such a pressure situation, solving the occurred problem often has a higher priority than documenting recent decisions and updating the system of objectives. In a little while, this circumstance leads to a vicious circle since an outdated documentation is not used or rather of any use, and a useless documentation will not be updated. Therefore, change and iterations in product development processes and their effect on systems of objectives have to be modeled easily and with little effort.

4 MODELING THE SYSTEM OF OBJECTIVES

A (textual) requirement document as it is common in engineering design practice (cf. to Hood, 2007) is often not suitable for handling the described complexity and dynamic of objectives in ways that user-friendliness as well as adequate and accepted performance is achieved. A poor benefit-cost-ratio especially results from problems depicting the relations between elements of the system of objectives and problems following changes and resulting iterations. Additionally, current existing methods are often too complex or poorly adapted to the special needs of the designers (cf. to Stechert and Franke, 2009). Albers et al. (2010a) presented an approach that uses the integrated product engineering model iPeM and a SemanticMediaWiki to depict engineering knowledge of whole companies as well as systems of objectives of single product development projects. They conclude that the used methodology was partly not accepted by the designers due to an insufficient understanding of the iPeM as a mental model, especially the differentiation between the system of objectives and the system of objects. Furthermore, they address problems concerning the integration of a knowledge-base and a project-specific documentation within one environment respectively tool. In order to overcome the identified issues, we claim to focus on modeling the system of objectives by using a lean methodology that addresses the main concepts outlined the section above and implementing this methodology with a simpler and more intuitive tool than SemanticMediaWiki. Due to these constraints, we decided to use a mind-mapping software-tool to implement the approach. We chose *MindManager Pro* from *Mindjet* because of the familiarity and availability in engineering design practice. Additionally, this particular mind-mapping software is very stable and sufficiently adaptable without major effort.

4.1 Hierarchy of Objectives

At the early stage of product development, the initial objectives are defined, typically by the management with information e.g. from sales and predevelopment. These initial objectives and their relations form the initial system of objectives which can be seen as the result of the early stage and the starting basis of the following product development process. Out of these initial objectives additional and refined objectives evolve during the further development process because more information about the characteristics of the product is gained. Hence, these objectives originate from the initial set of objectives and therefore, the initial system of objectives is the rationale for more specific objectives. This relation ensures the logical context and thereby the understanding and acceptance of the single objectives and thus of the whole system of objectives. This prevents the designers from pursuing wrong objectives, which e.g. remained in the system of objectives after the information basis changed for any reason. A way to include these relations is to depict the hierarchical structure of the objectives in kind of a dendritic texture where the logical connections between super- and sub-objectives are visible and traceable. Dendritic textures can be described in mind maps - every sub-objective is related to one super-objective via one distinct primary relation that indicates its origin and rational (cf. figure 2). This does not imply that there is always only one possible origin or rational for a sub-objective, but the approach forces the designer to decide unambiguous. The possible or rather expectable discussions between different designers on the right primary relation are desired and a positive side effect, since these discussions lead to an improved understanding of the system of objectives. The resulting model of the system of objectives is an intersubjective, shared conceptualization that represents the development task in a reduced and pragmatic way (cf. to section 2.2 and Stachowiak, 1973).

4.2 Relations between elements of the system of objectives

The presented primary relations between objectives allow modeling a hierarchy of objectives. In order to depict a system of objectives it is necessary to supplement this category by further relations and interactions between objectives. These secondary relations allow depicting supporting or competing objectives as well as other relations considered relevant. For example the objectives ‘low weight’ and ‘high strength’ conflict with each other on the other hand the objectives ‘low weight’ and ‘low moment of inertia’ supports each other. Secondary relations facilitate a wider understanding of the design problem - especially team members of differing disciplines are enabled to identify or add important relations by taking another point of view (cf. figure 2).

Thus, primary relations define the structure of the system of objectives and secondary relations add relevant information that extends the system of objectives beyond structural aspects.

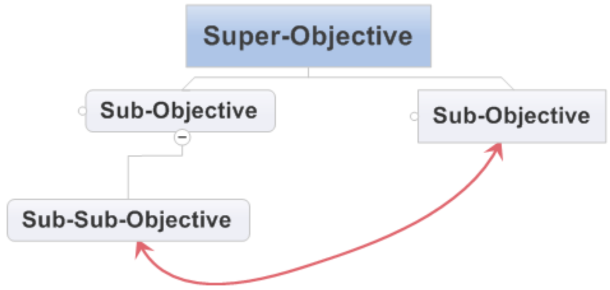

Figure 2. Elements of the system of objectives and primary/secondary relations

4.3 Dimensions of Objectives

The four dimensions of objectives contribute to establish a common mental model that helps to handle single objectives and whole system of objectives (cf. section 3.3). Furthermore the four dimensions can be used to explicitly add extra information to single objectives. Impact for example can easily be labeled on a predefined scale without the necessity to explicitly depict the underlying rational and consequences. Through this, different estimations from different designers of differing disciplines can be revealed and misinterpretation can be avoided. Rigidity is another important and useful dimension to easily explicate the available degree of freedom in the design process (cf. figure 3 and 4).
Every single dimension can be separately added and changed at any time if desired. Therefore, it is possible to increase the benefit of the model with little effort and without increasing the complexity of the approach itself.

4.4 Decisions, Change and Iterations

The process of product development is determined by changes, necessary decisions and potentially resulting iterations. Decision situations focus information and are highly coupled to the system of objectives (cf. Albers et al. 2010b). Decisions are made on basis of existing knowledge and existing objectives and entail either new objectives or invalidate existing objectives. They are either already made or are brought to a head in order to eliminate existing alternative procedures or solutions.
In order to depict a made decision and the underlying rational within a mind-mapping software-tool, every objective can be equipped with a note which contains the change history including the decisions and rationales in chronological order (cf. figure 4). This ensures that the objectives, past decisions and underlying rationales are always connected to each other. Alternative procedures or solutions can be depicted by adding an additional decision-element which subsumes the alternatives and indicates the necessity for a decision (cf. figure 3). There are two possibilities to depict a decision on alternatives that were explicitly modeled. Firstly, the decision-element as well as all alternatives can be deleted. Necessary to that, the rational of the decision has to be included in the remaining objective's note. Secondly, the decision-element is deleted and all except the chosen alternative become greyed out. Additionally, the rational of the decision has to be included into the objective's note.
A changing structure of the system of objectives can be easily depicted with little effort since the functionality of changing elements within a dendritic texture is a core-functionality of a mind-mapping software-tool and usually realized by drag-and-drop.

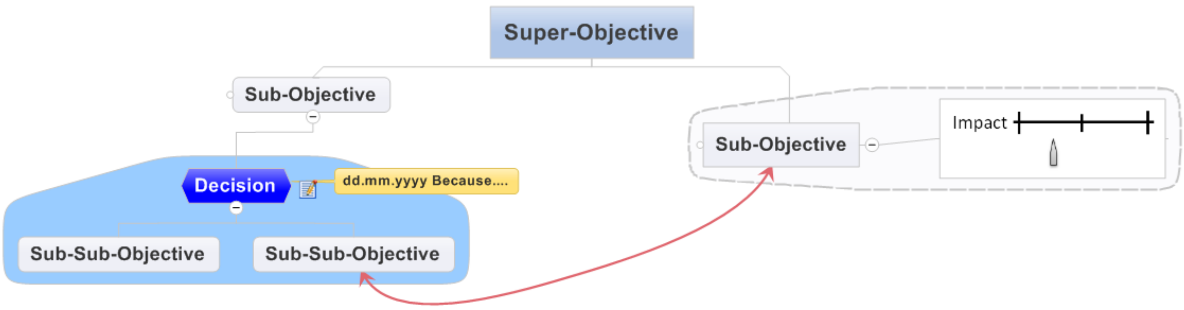

Figure 3. Dimension of objectives and decisions within the system of objectives

5 APPLICATION IN ENGINEERING DESIGN PRACTICE

The application and validation of the developed approach in engineering design practice took place in cooperation with one of the leading solution providers for the print media industry. In order to validate the approach with focus on user-friendliness and performance, we accompanied a product development project from the end of the early stage to the beginning of the production engineering. Uncertainty was still present due to a new and to date not introduced function principle which had an additional influence on the complexity of the mechatronic product. An initial system of objectives was already formulated and depicted in textual form – final technical solutions and details however were not defined yet. The development team consisted of four mechanical engineers including the project manager additionally supported by several experts of the domains electrical engineering and informatics.

The presented approach was implemented in the software *MindManager Pro* from *Mindjet*. Since this software was available at the company, it was already known to the designers and over a half of the involved designers had already used the software by themselves. Therefore, the obstacle of introduction was considerably reduced since the performance of the software-tool was generally appreciated. The mind-map-file depicting the project's system of objectives was mainly edited by one team member who was explicitly responsible for capturing and modeling the upcoming objectives. All other team members had access to the model. The file was stored in a distinct sub-folder of the project's network-structure which contained other folders and data e.g. datasheets.

Modeling the objectives did not start from scratch since an initial system of objectives existed in textual form. This document provided the basis for a model of the system of objectives in a mind-map representation. The hierarchical structure of the text-document could be directly copied and subsumed under a root node that beard the project's short description. Based on this model of the initial system of objectives, the system modeler arranged a first discussion with all members of the team in order to expand the model in terms of system elements and their relation. Additionally, the team members debated on the dimensions of certain selected objectives – especially on the dimensions 'impact' and 'rigidity'. In the following, the system modeler extracted new objectives especially from discussions with the project manager and from team meetings. The mind-map representation of the system of objectives was mainly consulted by the team-manager primarily in preparation for and after decision situations. He focused on two aspects. Firstly, the project manager examined the importance of the objectives by regarding their dimensions. Secondly, he called to mind the decision on alternatives that were still to be made. In the further progress of the project, several iterations occurred. Many of these iterations were comparably small with little impact and could be foreseen by the designers.

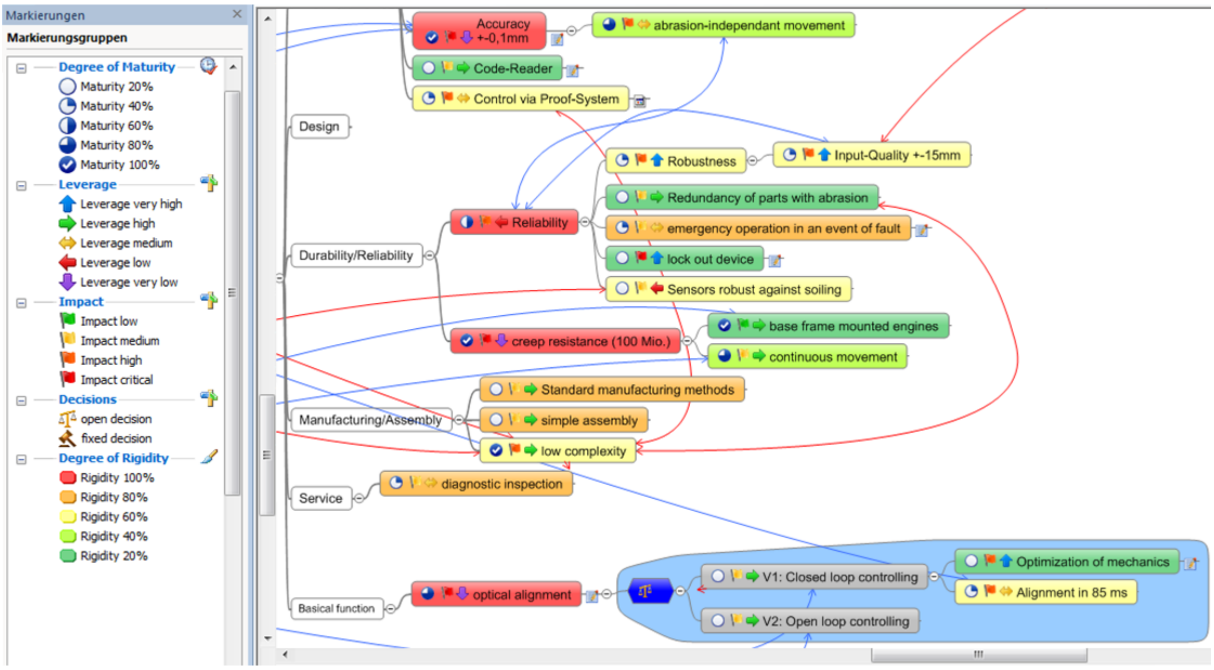

Figure 4. Implementation in MindManager Pro

Once only a major iteration occurred since the rigidity of an objective was evaluated wrongly and the available degree of freedom including the resulting opportunity lay idle. These iterations and the increasing maturity of the system of objectives resulted in several structural changes within the mind-map which became necessary in order to ensure the performance of the model. Figure 4 shows an excerpt of the system of objectives depicted in *MindManager Pro*.

6 DISCUSSION

With the help of the presented approach implemented in *MindManager Pro* it was basically possible to model the system of objectives in engineering design practice and herewith to create an additional value in comparison to a static textual representation.

The designers strongly agreed with our presented insights from literature review and own research, especially concerning the dynamic and complexity of system of objectives and the necessity for an improved handling in engineering design practice. The designers were able to understand our basic approach and its implementation in *MindManager Pro* and since they were mostly familiar with the chosen software-tool they were very open-minded about our approach. The explicit separation of primary and secondary relations enabled the designers to transfer their understanding of existing requirement documentations (primary relations) and facilitated the usage of secondary relations as additional information that extends the system of objectives. The existing initial system of objectives represented in textual form could be easily and comprehensibly transferred and allowed a revealing discussion on additional objectives and secondary relations that increased the understanding of the design task and its challenges. In the further product development process the maturing system of objectives could be easily depicted by adding new elements and relations to the mind-map and thus extending the representation. The designers appreciated the good overview of the current system of objectives due to the graphical representation – especially compared to a simple textual representation. Furthermore, they emphasized the benefit of the explicitly depicted rationales that can be added to single objectives via note since they create a wider understanding of the purpose of each objective. The dimensions of objectives were regarded ambivalently by the designers. “Impact” and “rigidity” on the one hand, were highly appreciated since these dimensions created an improved understanding and communication of single objectives in terms of priority, interdependency and changeability respectively degree of freedom. On the other hand, “maturity” and “leverage” caused misunderstanding. “Maturity” was considered synonymous to “rigidity” since in engineering design practice “maturity” and “rigidity” usually rise synchronal. The concept of “leverage” was mostly understood by the designers but they saw no real benefit in depicting this particular dimension explicitly. According to the involved designers and especially according to the project manager, the dimension “impact” and “rigidity” combined with an overview of the open decisions on alternatives helped to steer and regulate the design activities by improving decision making (cf. section 5). In order to ensure the usability of the mind-mapping representation, the mind-map needed to be restructured several times which decreased the overall benefit-cost-ratio as well as the performance of the approach. Performance could be additionally decrease by two other challenges. Firstly, the pure amount of objectives can lead to a confusing mind-map representation. Secondly, it could become necessary to describe single objectives more in detail, which is hardly possible at the moment.

Although the validation of the approach in engineering design practice revealed room for improvement, the project manager is up to date, six months after our project ended, still working with the mind-map-representation.

7 CONCLUSION AND OUTLOOK

Modeling systems of objectives in engineering design practice is a challenging task. This paper has argued that the multitude of objectives is interrelated and forms a system of objectives which is affected by change and iteration. We have shown modeling the system of objectives requires an adequate reduction and pragmatism in order to ensure user-friendliness, performance and acceptance in engineering design practice. We deduced a lean methodology for modeling the system of objectives and proposed an implementation in the intuitive software *MindManager Pro*. The results of an application in engineering design practice imply that the approach is user-friendly and mainly accepted by designers in practice; the performance however has to be further improved.

Further research focuses on analyzing appropriate structures and views of the system of objectives. Additionally, an enhanced modeling methodology is required that offers user-friendliness and adequate performance in order to ensure acceptance in engineering design practice.

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