Life-Cycle Oriented Requirement Formalization and Traceability

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Abstract. Fast changing environment put huge pressure on companies, which have to develop products increasingly faster in order to stay competitive. Change propagation in requirements engineering and life-cycle-management is a key competency to increase the efficiency of product planning. We propose a method using structural complexity management methods to achieve consistency between these two domains. Requirements modules and life cycle planning have been connected by matrix subtraction in order to identify changes in both domains. The result is an increased level of transparency of the regarded system. Additionally, traceability of change for supporting product planning in the early phases of a design process is enhanced.

Keywords: Requirements Engineering, Life Cycle Phases, Structural Complexity Management, Requirements Module, Change Propagation

1   Introduction

Companies face a fast changing environment in which demands and solutions for new products have to be carefully analyzed and evaluated. In order to stay competitive, companies need to choose the right combination of functions and technologies and have to be able to bring them into the market the most economically way possible. With shorter life-cycles, companies are forced to bring products to market maturity even faster [1]. Further, time or planning horizons for new products need to be synchronized carefully. This way, it is possible to develop and to align new competencies efficiently.

The paper at hand addresses the problem how to support the decision making process by improving the transparency during the planning of new products. The idea is to visualize and document dependencies of product artifacts along several product life

cycles. Hereby the focus is laid on the different life cycles and their phases which need to be aligned for a better utilization of the resources of companies. Hence, there are several planning activities, which need to be taken into account.

- The analysis of impact factors outside and inside the companies which have influences on the properties of a product itself and its life cycle [2].
- The forecast of new products in short-, middle- and long-term horizons. Additionally, their alignment by identifying the dependencies among different planning horizons [3].
- Documenting changes in the properties of products and their successors [4], [5].

The paper proposes a life-cycle oriented formalization of requirements on various levels of concretization in order to improve transparency and traceability during innovation processes (especially planning and design) [6]. Therefore, requirements are combined with life-cycle phases. Changes in the intended properties of a product can be traced to the life cycle and taken into account in the life cycle planning. Further, an approach for the improvement of the actuality of requirements should be presented.

The paper will provide a framework for the planning stage of new products in which changing environment factors are analyzed for their influence on given and future products. This will be done by describing a three staged process which is demonstrated at the end by an example in the automotive industry.

The major goal is to improve knowledge management in a company and to support existing PLM-tools and methods [7] by change propagation. The requirements module is designed to provide a formalized interface between requirements management and its influencing information sources like marketing or after sales. Additionally, change matrices support dealing with changed information basis through localizing out-dated knowledge in requirements.

The addressed problem was identified during the project in the automotive industry which has the goal to analyze the impact of technology changes in the requirement elicitation of new car models. With the radical change/enhancement of the power train towards electrical powered solutions, given specifications are partly outdated and need to be designed according to newly introduced technologies in this field.

Further, various cycles during the innovation process of products are addressed in the collaborative research center 768. Hereby, keeping requirements up-to-date is a pressing matter which needs to be taken into account for an integrated planning process under consideration of iterative and recursive cycles.

The research questions which should be answered in this paper are:

- How changes of properties of a product can be used to improve the anticipation of the product life cycle?
- How can this change be documented and measured consistently in product specifications?

In order to deal with these questions, some basics need to be introduced. Firstly, it is built on an integrated life-cycle model which allows for a detailed granularity of time-depended relations between life-cycle phases. Secondly, the approach is based on

methods developed in structural complexity management. Up-to-date research in this field supports tracking of changes in the properties of products and therefore allows for data-based conclusions connected to changed parameters regarding the properties of products [8]. Third of all, requirements engineering provides tools and formalization for documenting detailed changes in the properties of products [9], [10]. In sum, these three fields are combined in the next chapter into the framework for life-cycle oriented requirements formalization.

1.1 Life-cycle

During the planning of new projects, decision makers need to take into account the anticipated life-cycle of the product at hand. This makes sure that the new product is planned according to the given resources of a company and that the life cycle phases of other products are not crossed negatively. Planners have to synchronize design processes because of limited resources when i.e. just one product could be developed at a time-period. Additionally, substitutive products are not favored at the same time on the market.
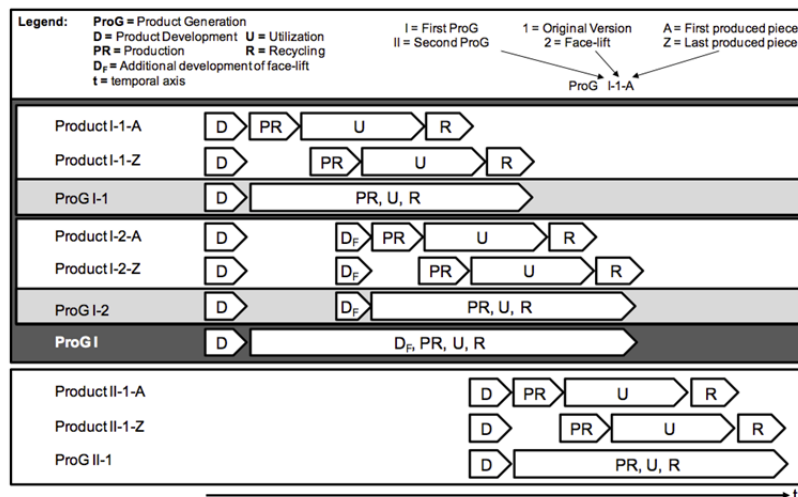

Fig. 1. Scheme of multiple subsequently following lifecycles [13]

The lifecycle model [11] which is considered in this paper consists of the phases of 'Product planning', 'Product development and design', 'Production process preparation', 'Production', 'Distribution', 'Utilization', 'Maintenance', 'Modernization lifecycle' and 'Product disposal'. These superordinate phases are further split down to more than 25 working phases and more than 15 product states. For reasons of clarity, in this paper, we will just consider a generic life-cycle model composed of the phases design, production, usage and disposal. The fragmentation of the life cycle phases in the proposed methodology can be extended or adjusted to a company's implemented innovation process.

Fig. 1 presents an example how various products and their phases can be broken down. In this case, there is depicted a product generation followed by an exemplary face-lift and the successive product generation. The phases of the life-cycle are depicted without overlappings in a single life-cycle, which supports clarity in this matter but is to be found in literature also differently [12].

1.2 Structural Complexity Management

Planners need to consider different perspectives of a product during the planning phase. An auspicious approach is structural complexity management (SCM) [14]. With its help, it is possible to analyze and visualize different relationships of so called domains or classes of elements in systems engineering. The main part consists of dependencies or relations between two elements are depicted through graphs and/or matrices. The analyzed elements and their relationships between each other can be derived from one or more domains. Elements out of one domain are visualized in a design structure matrix (DSM). Dependencies between elements of different domains are demonstrated in domain mapping matrices (DMM). The regarded system in a whole is illustrated by a multiple domain matrix (MDM) which is built of DSMs and DMMs. The methodology supports system analyses and enhances the understanding of systems and their behavior. Structure analyses and changes within can be documented transparently and it is possible to track changes in the system (e. g.: changed environmental influence factor on chosen materials). One method utilized in this paper is the use of change or delta-MDMs [15]. Through marking dependencies within the MDM by '0' and '1' and using matrix algebra, the comparison of two MDMs results in a change MDM. Hereby, changes in elements or dependencies are documented and can be used for further analyses (see Fig. 2).

In product planning, the methodology provides a tool for displaying the difference of a system between two time periods [8]. Hereby, changes in a product can be depicted or the comparison between two different products can be carried out.
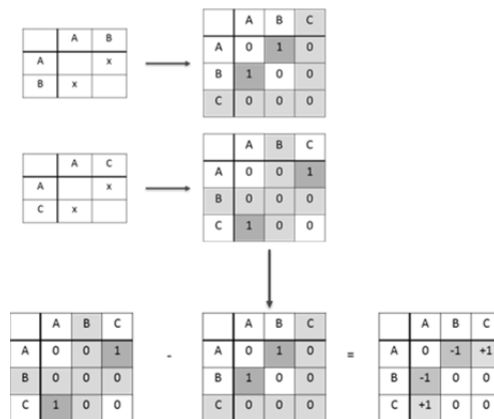

Fig. 2. Development of the change-DSM

1.3   Requirements formalization

Requirements engineering (RE) supports the elicitation and documentation of product properties through artifacts which describe the product on various levels of concretization. Beginning with the documentation of high-level product characteristics like goals and market demands, continuing with mid-level product requirements and finally ending with low-level system or subsystem requirements, RE provides a holistic approach for dealing with product properties. Additionally, it provides traceability through the design process. Changed artifacts on every level of detail can be traced back to the reason of change or forward to the resulting implications. The right choice of attributes describing a requirement is essential for an effective use of RE. Entries like high-level-target, described function or the background information are just examples for attributes which ease the traceability of changes [16].

In order to be able to plan new products and their life-cycle, a planner needs to be aware of the dependencies in the products, he is responsible for. Fig. 3 shows an example of how a requirement can be formulated:

2   Methodology

The methodical approach is inspired by the work in the collaborative research center 768 which deals with reoccurring patterns along the innovation process and systematically acquired experience during the work with industrial partners. The authors propose a three-phase process model for extracting product-relevant information regarding future product life-cycles and its different time periods as well as the integration of information in a formalized requirements model. Hereby, the process model provides a transformation of information gathered from the environment into product-specific requirements. This suits the consistency of planning information in the early phases of the innovation process [18]. The process model is built out of three main phases: analysis and transformation and documentation. The analysis phase examines changes according to existing planning data like life-cycle roadmaps or scenarios based on SCM techniques. Thereby, the planned life cycle of a future product remains a major focus. Further, the transformation phase identifies the type and extent of changes with the help of matrix comparison. The results illustrate the needed changes in the specification lists. Finally, the identified changes are allocated to the correct requirements modules and updated accordingly in the life-cycle planning. In the end, the planner attains a goal-consistent document which describes the future product from both a requirement perspective and a life-cycle phase. These three phases should be described in more detail.

So it is stated, that a formal elicitation process consist of documented goals, requirements and specifications within a requirements module. Further, the increasing concretization of goals through product requirements to system requirements are interconnected and this way present to the planner. An abstract example for this is depicted in Fig 3. It mainly consists of the different concretization levels of requirements and some independently selectable attributes. Further, the involved and influenced life cycle phases are integrated. It is even possible, to extend the requirements

module with information about the extent of influence on the life-cycle planning (here depicted with the generic term "integration challenge).If all these requirements modules are combined, it results in a specification list, which is common tool in the industry nowadays.

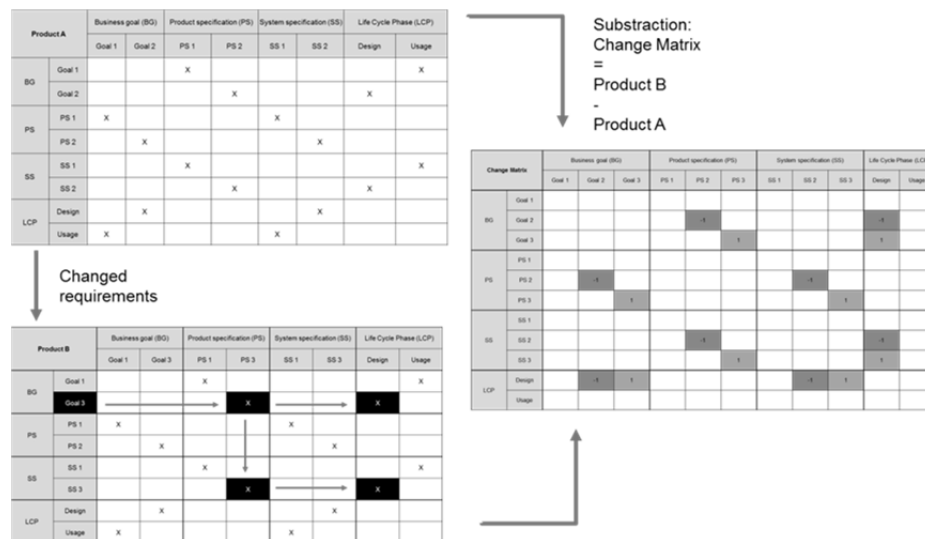**Fig. 3.** Life-Cycle-Orientated Requirements Module

Fig. 4. Calculating the change matrix

The categories of the specification list result in the depicted domains of a matrix. As soon as the specification list is analyzed for the documented connections between high-level-goals and low-level specifications within the requirements modules, the entries in the specification list matrix can be inserted. This is normally done by a dimensionless character like an "X". The result is an analyzable depiction of the product during the product design. With further design projects, this documentation marks an efficient artifact to identify changes through different concretization levels.

As for now, future product changes in the various domains can be analyzed for their impact in the characteristics of a product. Exchanging blank entries with "0" and dependencies with "1", the matrices are transformed into calculable pendants. Further, the matrices are extended with the elements from the other matrix, so that the two matrices become congruent. Through matrix subtraction, the change matrices of the current and future product can be identified and so be documented for further design activities and decisions.

The resulting delta or change matrix depicts the changes in the different concretization levels of the analyzed product. Depicted here in Fig. 4 is just a change-DSM, which easily can been extended with more domains. The methodology remains the same. The values "-1" and "1" are interpretable as the former and the new elements in the matrix. These changes can be identified and traced in the specification list and the connected requirements modules. Through these updated requirements modules and in sum the specification list, the life cycle plan can be updated.

3   Results

The applied methods from RE, life cycle management and SCM result in an integrated framework for the handling of changes during the planning of new products. Requirement changes and their impact on the product can be traced back on different levels of concretization through the utilization of requirements modules. The integration of life cycle information in these requirements modules connects life-cycle management to RE. Changes within a requirement module are analyzable for their impact on requirements in other hierarchy levels. Through the use of matrix algebra, independencies between requirement modules of different product projects can be identified and depicted for further analysis [17, 18]. By the amount of change and the involved domains, it is possible to state the extent of change propagations through changed requirements. Further, traceability of changes works in both ways in all selected domains as the dependencies in the matrices are marked symmetrically and therefore are also retrievable in the change matrix. The attributes in the requirements modules and the planning of life cycle have been connected by matrix subtraction in order to identify changes in both domains. The result is an increased level of transparency of the regarded system. Additionally, traceability of change for supporting product planning in the early phases of a design process is enhanced.

3.1 Case[1]

Following the proposed frame work will be shown in an applied example from a project in the electro-mobility sector of the automotive industry. This branch of industry is working with the reuse of requirements because of a high number of iterative projects. In the last years, the increasing number of variants put pressure on the planning and development departments to increase the efficiency in the project planning of new car models. Additionally, technology leaps like solutions for satisfying the increased interest in electric mobility made historical requirements of components obsolete in new mobility concepts. Therefore, handling change propagation becomes a focus in this industry.

The goal was to develop a method for handling requirements in a way that changes could be traced in the requirements lists. Thereby, the amount of rework in the different concretization stages of the requirements could be anticipated and planned beforehand by having a better picture of how much time a planner would spend to update an outdated requirement.

Change		BG		PS		SS		LCP	
		Low Consumption	Electrical Power	Cruising Range A	Cruising Range B	Fuel Storage	Energy Storage	Design	Usage
BG	Low Consumption			-1					
	Electrical Power				1				1
PS	Cruising Range A	-1				-1			
	Cruising Range B		1				1		
SS	Fuel Storage			-1					
	Energy Storage				1				
LCP	Design								
	Usage		1						

Fig. 5. Change matrix of exchanging a fuel tank for a battery

Here, the example is the description of the energy source for a common and an electrical powered vehicle. Both requirements modules end up in the description of the tank capacity of a common tank and in a description of the amount of energy stored in a battery by setting the number of standardized energy cells. The changes in the requirements module for the energy source were then demonstrated in the change module see Fig. 5. This way, it was figured out that the elicitation of the correct amount of energy cells was to be considered. Even more interesting was the fact that the new requirement was affecting not only the design phase but also the usage phase (to be seen by "1" in the "Usage"-column in Fig. 5). The choice of the value of the battery capacity had a direct influence on the usage phase, because the life-time of the battery was dependent on it. The unlimited reuse of a petrol tank was exchanged through a battery with a foreseeable life-time.

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[1] Data shown in this case study has been modified due to confidentiality reasons.

4 Conclusion

Fast changing demands in markets and radically evolving new technologies pose great challenges to companies. An approach for dealing with this is staying flexible within the company`s product portfolio in order to be prepared for unforeseen changes in the environment. Further, companies should scan future opportunities of product designs in order to be prepared for predictable changes. As requirements represent a possible way for the transformation of information and knowledge into boundaries for designers, it is essential that they are as consistent as possible. Product descriptions depend on a formalized representation of goals on various levels of hierarchy. Each of these goals can be structured in the presented requirements module which represents a structured but flexible unit, in which information relevant for transparency and traceability is included. The modules' attributes are designed in a way that they are useful for dealing with a changing environment. Especially, the validity and actuality of a requirement from a life-cycle point of view are documented in a requirement module. By methods from SCM the static approaches like a change history in RE can be supported. The utilization provides an enhancement in dynamic interdependencies in life cycle management and RE.

By analyzing the future and dedicating time slots to future scenarios, it is possible to establish a picture of future products. Further the comparison with former planning cycles enables planners to assess the impact of the change to the own company in terms of required resources or competencies. Finally, these changes can be integrated precisely into existing project planning processes by identifying and updating requirements.

4.1 Outlook

Further research will be conducted in analyzing the opportunity of enhancing the reuse of requirements. In this case, it is of interest, how a requirements module needs to be structured in order to depict changes on different levels of reuse. Additionally, there is a demand for identifying algorithms to support reuse automatically through metrics derived from experienced change propagation.

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