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LIFE CYCLE DEVELOPMENT - A CLOSER LOOK AT STRATEGIES AND CHALLENGES FOR INTEGRATED LIFE CYCLE PLANNING AND UPGRADING OF COMPLEX SYSTEMS

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Abstract

Life cycle development provides a framework for methods and strategies to develop a product and its related processes regarding technical, economic, ecological and social properties over the whole life cycle. Several disciplines are involved to plan, design and implement the product life cycle. This contribution states that current modelling approaches are mostly driven by one discipline and, thus, focus on certain groups of modelled properties. It is hypothesized that integrated modelling approaches, combining the interests of the parties involved, have to be developed to display the properties and their relations in one model. This paper first introduces the life cycle development framework and existing methods to support the phases of planning, design and implementation. Two needs for further research are derived and motivated, addressing certain excerpts of life cycle development: (I) an analysis of existing modelling approaches in life cycle planning, aiming at the detection of links between these approaches and developing integrated models; (II) an approach to integrate software and hardware modelling with the aim of extending a mechatronic product's life time.

Keywords: Integrated product development, Product life cycle development, Life cycle planning, Design for X (DfX), Sustainability

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1 INTRODUCTION

Product development in industry often focusses on the properties required during the use phase of products. Customer satisfaction and profitability are often seen as the most favored criteria to meet. However, there are numerous approaches to cope with properties of other life cycle phases like manufacturing or end-of-life. Increasing awareness of limited resources leads to legislation and directives. Furthermore, a growing relevance of sustainability for users leads companies to reduce the environmental impact of products over their life cycle. For instance, there are restrictive targets for reuse, recycling and recovery of end of life vehicles (European Parliament, 2000) or guidelines for minimum life time of electronic products (European Parliament, 2009). Furthermore, companies strive to achieve role model function with "green production" or "green products" by changing product and production strategies. These legislations, directives and strategic aims lead to a paradigm change in business strategies and product development. Therefore, several approaches for developing sustainable products are described in literature (Niemann *et al.*, 2009). However, these approaches mostly represent a single discipline's perspective, like engineering design, production engineering or economics and therefore focus on a limited number of product properties.
Differing objectives within these disciplines lead to goal conflicts during the development, but are often not revealed at the time the relevant properties are handled in discipline specific models. This mismatch results in weak points of products and processes in terms of technical, ecological, economic or social properties and often leads to a non-achievement of the objectives defined initially. Based on these issues, a need for action can be derived concerning an integrated view upon products and processes over the whole life cycle. In order to provide this view, communication between the actors involved in product life cycle development has to be improved, addressing the different and differing objectives of the parties. Therefore, approaches for the integrated and holistic modelling of products and processes are required. The aim of this contribution is to highlight the need for integrated modelling approaches introducing one approach for life cycle oriented planning and one approach to extend the use phase of mechatronic systems exemplarily. Based on these approaches, needs for further research will be derived.
The paper is structured as follows. In chapter 2, an established framework for life cycle development (LCD) is presented and existing methods to support the different steps are introduced. Based on this state of the art, the two approaches will be described in chapter 3 and need for research will be discussed. In chapter 4, the content is summarized and an outlook for further research is given.

2 FUNDAMENTALS AND METHODS OF LIFE CYCLE DEVELOPMENT

Based on the motivation for life cycle oriented product development, chapter 2 deals with the fundamental understanding of life cycle development. Therefore, a comprehensive framework proposed by Umeda et al. (Umeda *et al.*, 2012) has been chosen to describe the main phases of the interdisciplinary life cycle planning (LCP) as well as the design of products and processes to implement the life cycle.

2.1 A Framework for Life Cycle Development by Umeda et al.

The framework shown in Figure 1 provides a basic understanding of the actions carried out by the various parties during planning, design and implementation of products and related processes. This overview displays the range of actions from strategic decisions in planning, detailed drafting and design of the product and processes during design, culminating in the execution of the product life cycle.

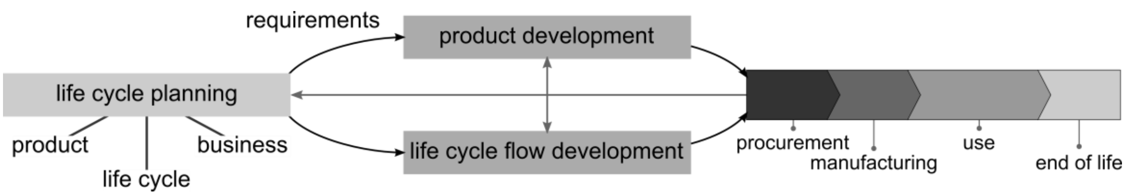

Figure 1. Framework for life cycle development, following (Umeda et al., 2012)

Umeda et al. postulate that, during LCD, two interrelated views can be taken: On the one hand, the product with all its properties and characteristics has to be defined. On the other hand, processes needed for producing the product, as well as related processes during use phase and end of life, have to be determined. Within the planning phase, both product and process view have to be treated in an integrated manner in order to predefine the direction for the ensuing development. In the design phase, engineers are called to work out solutions for the product with regard to the product architecture, the technologies used as well as different strategies, e.g. to support maintenance or modify the product during use phase. In parallel, production engineers have to define all related processes forming the product's life cycle flow. For instance, the supply chain and detailed properties of manufacturing and services have to be defined. During the implementation phase, the designed product and processes are merged, required manufacturing processes or supply chains are worked out. The diverse phases within this framework highlight the importance of the integration of different views upon products and processes in order to address technical, economic and ecological criteria during decision making.

Further sections will describe the phases in detail. As life cycle planning and product design from life cycle perspective will be relevant for the two presented approaches, an overview of strategies and methods for these two phases is given.

2.1.1 Life Cycle Planning

Life cycle planning is a strategic phase, aiming at the holistic technical, economic and ecological development of a product and its life cycle flow. The planning phase can be divided into three steps (Umeda *et al.*, 2012) (a) target setting, (b) life cycle strategy planning and (c) evaluation. Target setting includes scoping of the product life cycle, taking all external and internal factors like customer needs and company strategy into account. Approaches with focus on product strategy, as presented e.g. in (Hauschild *et al.*, 2004), support a systematic planning. Furthermore, checklists, as shown e.g. in (Wimmer *et al.*, 2004) and (Kishita *et al.*, 2010), are provided for eco-assessment of a predecessor or concurrent product. Within life cycle strategy planning, the basic concepts of *product concept* (functional, environmental and cost requirements), *life cycle options* (for product, assemblies, components and material) and *business options* (product delivery, business model and balance of product and service) are developed. One method for determining the product concept is the Quality Function Deployment with focus on environmentally relevant aspects (Masui *et al.*, 2003). Also, function-behavior-state modelling as described by (Umeda *et al.*, 2005), focusing on the integration of upgradability strategies and the definition of use cases and stakeholders, supports the definition of the product architecture. Another tool to define life cycle options is proposed by Tani (Tani, 1999), describing the comet circle, indicating the environmental impact depending on steps for different end-of-life strategies. Furthermore, a concept with scope on reducing disposal cause is described by Umeda et al. (Umeda *et al.*, 2003), followed by an approach of Kobayashi (Kobayashi, 2005) called LCPlanner. This approach integrates strategies from production and collection plan, business requirements as well as the product's value and useful life time in order to evaluate the right life cycle options. Business options can for instance be set using eco-business rules (Nakamura *et al.*, 2012). Kondoh and Mishima (Kondoh and Mishima, 2010) expand these by the total performance indicator, describing the balance of customer utility value, its resulting environmental load and cost of the product. Furthermore, criteria from each of the involved disciplines are derived as a basis for evaluation, for example on costs over the whole life cycle. Life Cycle Costing and Life Cycle Assessment are well established methods for analyzing and determining costs and ecological impacts, respectively (Verein Deutscher Ingenieure, 2005; Brissaud and Zwolinski, 2004). An approach integrating the analysis of economic and ecological aspects called Material Flow Cost Accounting is presented by (Jasch, 2009).

Each of the presented modelling approaches addresses a certain amount of properties of the product and processes. A broad overview including further methods is given by Umeda et al., classifying papers in life cycle development, starting from 2003 (Umeda *et al.*, 2012). However, there is no approach integrating all properties that are defined during planning, integrating all different views involved.

2.1.2 Product Design

During the product design phase, the product engineering tasks, like determining functions, detailing the product architecture, generating CAD models or realizing software components, are conducted (Grote and Antonsson, 2009). Umeda et al. (Umeda *et al.*, 2012) emphasize the necessity to consider the life cycle perspective in particular and to apply special Design for X (DfX) methodologies like Design for Environment (Fiksel, 1996), Design for Assembly (Boothroyd, 1987) or Design for Disassembly (Harjula *et al.*, 1996). The superordinate goal of this phase is to develop a product complying with customer requirements and the economic expectations of the producer with simultaneous consideration of ecological aspects. Such methodologies are, e.g., addressing aspects like Design for Product Reliability (Kimura *et al.*, 2007), Design for Remanufacturing (Nasr and Thurston, 2006), Design for Maintainability (Stapelberg, 2009) or Design for Modularization (Seliger and Zettl, 2008). All these methodologies are focusing on a specific subset of product properties and the related processes. Therefore, it becomes a major challenge to address all required properties of the product to be developed. With regard to mechatronics, a further challenge is to define a suitable product architecture considering the functional and spatial partitioning of the system (Welp and Jansen, 2004). In order to substantiate decisions, it is necessary to model the product from both functional and structural view point, addressing specific aspects of hardware and software engineering as well as their interrelations. Needs and challenges of an integrated system modelling will be highlighted in section 3.2.

2.1.3 Life Cycle Flow Design

The life cycle flow design phase focusses on the determination of processes, relevant for the product life cycle flow, like manufacturing, logistics, maintenance and recycling processes. In doing so, a distinction concerning processes in Beginning of Life (BoL), Middle of Life (MoL) and End of Life (EoL) is often made. Compared to life cycle option planning, similar approaches can be used, but with a more detailed knowledge level. As shown in sections 2.1.1 and 2.1.2, all of the approaches presented have in common that only a specific group of characteristics of product and processes is modelled.

2.1.4 Implementation

The implementation of the product life cycle includes the organization and execution of the product life cycle and, thus, the transformation of the planned and developed product life cycle into the real world. An example for a certain activity in this phase would be a manufacturing process and - with regard to the external factors that may occur - reacting to problems in the supply chain, for instance delivery problems for material or semi-finished products. Additionally, processes during and after the use phase, like services and recycling, are executed in this phase.

2.2 Derivation of Needs for Action

For the phases presented as well as their correlated actions within the framework of LCD, several methods, tools and models exist, mainly emerged from the disciplines product development, economics and production technologies. Predominantly, they are discipline specific and used to model only a certain amount of properties of a product or processes. Across all phases, there is a common challenge: For a better coordination of all actors in life cycle development, interdisciplinary approaches have to be developed. Thus, in addition to the approaches mentioned before, further needs for research can be derived, leading to the questions:

- How can the perspectives and criteria of different disciplines be handled within LCD?
- How do models support an integral view on products and process for different strategies of LCD?

In this contribution, two further approaches will be discussed to highlight the need for an integrated view and analyze existing methods and models to support these. The interdisciplinary approach for planning is especially important, since actions are taken out to determine the product concept as well as business and life cycle options. The second interdisciplinary approach addresses the design phase and focusses on possibilities for extending product use phases by raising the customer benefit during its life.

3 RESEARCH APPROACHES

In this chapter, two independent research approaches will be introduced, addressing the topic of integrated modelling within the two different phases of life cycle planning and design. The first research approach addresses the phase of life cycle planning, as it is stated to be one of the most relevant steps in life cycle development because of the high importance of strategic decisions in the beginning (Umeda *et al.*, 2012). The second approach addresses the product design phase. It aims at extending the use phase of complex mechatronic products, focusing on the upgradability of existing systems considering interrelation of software and hardware subsystems as well as their related innovation cycles.

3.1 Integrated Life Cycle Planning - Needs and Approach

Since life cycle planning has a great impact on technical, economic and ecological properties of products and processes during the whole life cycle, understanding of actions and interactions in this phase is elementary to bring up sustainable products. The aim of this approach is to identify major challenges of the interdisciplinary product and process planning and to derive further needs for research.

3.1.1 Life Cycle Planning - Objective and Perspectives

The importance of planning is undeniable for a successful life cycle development, since the overall direction for product and processes is defined in this phase. Thus, the aim of planning is to include all relevant scopes and targets from the different perspectives on the product life cycle into account. Figure 2 shows an exemplary diagram, representing a target system to evaluate four superordinate categories of criteria of the product life cycle. The specific company strategy is the decisive guideline for weighting several criteria (determining values between 0 and 5 in the radar chart for each criterion). In this target system, the dashed line shows a scenario in which technical, economic, ecological and social criteria are weighted the same, forming an equal rectangle in the radar chart given. A more realistic than idealistic case for the importance of the categories is shown by the continuous line, indicating that, for a better score of one category, e.g. economics, others have to be neglected. However, the question remains what specific models are used to evaluate the presented critetria and what product and process properties are allocated to the criteria. This question highlights the need for understanding modelling within LCP.

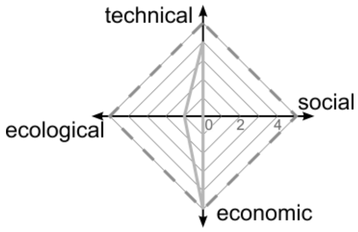

Figure 2. Model for the evaluation of a product life cycle with four categories of criteria (relative scale). Dashed line: balanced; continuous line: realistic weighting of criteria

3.1.2 Modelling in Life Cycle Planning

Providing a fundamental understanding of why the original objectives of a company might not be met, an analysis of existing modelling approaches within planning has to be carried out:

- Which are the parties involved in LCP and what are discipline specific targets and models?
- What are existing modelling approaches within planning and what purposes are they used for?
- What objects and relations are modelled in the presented approaches?

This analysis is supposed to lead to a simplified model morphology following (Buur and Andreasen, 1989), classifying and linking the approaches according to their modelled objects, purposes and disciplines involved. In the following subsections, these first questions will be answered for some exemplary approaches as a first suggestion of how the analysis has to be built up. As a basis for the analysis, the widely accepted design theory of Weber is used (Weber and Deubel, 2003). It distincts between properties and characteristics, connected by relations. Since only characteristics can be directly affected by the designer, the properties are resulting by these through an allocation of relations. Assuming that this theory is applicable not only for a product's properties, but also for processes', in this contribution it is used as a generic basis for product life cycle modelling from different perspectives. Figure 3 illustrates that three actors are working in parallel, using various models (relations) to transform characteristics into properties. The selection of characteristics and properties (and thus, models) corresponds to the particular parties' requirements and modelling purpose. It also shows that it is possible that two actors are defining the same property with differing goals (in this example a part's weight).

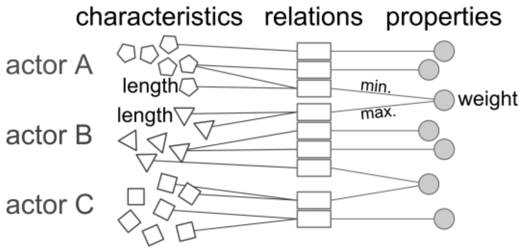

Figure 3. Several actors in parallel define sets of properties from different perspectives

An example in the scope of defining the product concept are physical correlations, like a rough estimation of a product's life time. Furthermore, from the economic point of view, the approximate amount of material used in combination with a lump sum depending on the manufacturing process gives an indication of the material cost for a part. An example for life cycle option modelling would be the evaluation and comparison of possible scenarios for reuse by modelling rates of return parts or products. The following subsections will provide an overview of a first analysis conducted.

Table 1. Analysis of different models in life cycle planning. (DCA: Disposal Cause Analysis)

Approach	**Objects and relations**	**Purpose**	**Users/Disciplines**
1) QFDE (Masui *et al.*, 2003)	customer needs, "stakeholder environment", product requirements from different disciplines (technical, ecological, economic); relations between stakeholders' needs and requirements	specify (customer needs, conditions) define (requirem.), evaluate (importance of requirements)	mainly product concept planner, supplemented by the ecological perspective
2) DCA + value & physical lifetime (Umeda *et al.*, 2007)	value lifetime, physical lifetime, disposal distributions; relations between the ratio of value and physical life time and life cycle options	define (life cycle options)	focus on the life cycle flow
3) LCC (Verein Deutscher Ingenieure, 2005)	quantitative: relevant cost over the whole life cycle; qualitative: other factors, not quantifiable in monetary terms (e.g. delivery time, market position of suppliers,…); relations between identified costs and investment decisions	describe (cost over life cycle), evaluate (cost, equipment, maintenance strategy)	focus on the economic perspective

Summarizing the analysis presented in Table 1, it is apparent that some approaches, such as DCA, are discipline specific and focus on a certain group of properties, belonging to one of the properties shown (technical, economic, ecological and social). Others already include more than one category of properties, e.g. the interests of classical product requirements expended to ecological aspects. This indicates, that further interdisciplinary approaches can be found and relations between the approaches can be detected. Clearly, the commenced analysis of existing modelling approaches in life cycle planning has to be extended in future work. Further modelling approaches, e.g. from Systems Engineering have to be analyzed in detail to get a meaningful and significant picture of the "linking map" of approaches in planning. In this paper, the shown approach for the analysis forms the first step of research concerning an integrated LCP.

3.1.3 Research questions

Challenges in setting the life cycle strategy can be found in the merger of the before mentioned groups of characteristics, combining the different objectives. In case that two (or more) characteristics have an impact on one property, or are of interest for more than one stakeholder, often goal conflicts occur. (Inkermann and Vietor, 2016) It is possible that two or more parties try to modify the same characteristic without knowing they're not the only group of interest concerning this characteristic. The aforementioned difficulty of interlocking and competing characteristics and properties can't be solved easily and poses a big risk in planning, jeopardizing the well-balanced performance of a product life cycle. Figure 4 proposes the idea of how interactions between the actors' targets can be revealed and made transparent to every of the parties involved. The idea is to uncover relations not only between characteristics and properties, but also between models which are used to determine the required properties. The network of models, including information on the transformation of characteristics into properties (and vice versa), is depicted in Figure 4. It is also indicated that the result of product and process modelling at the end of the planning phase can be visualized in a radar chart as an overall picture.

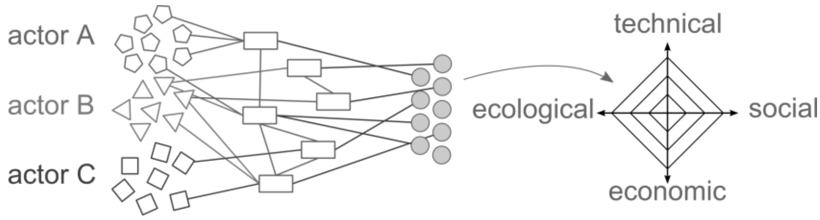

Figure 4. Possible network of relations (models) between characteristics and properties

In further research work, this assumption of a network of characteristics, relations and properties is taken as basis to describe and detail the depicted connections. The following research questions were defined to set the common thread for a systematic analysis keeping in mind the preliminary questions for the analysis of modelling approaches.

- How can models (of interest for different disciplines) be related to each other?
- How can the knowledge of intersections/goal conflicts be used to improve life cycle planning?
- What requirements for integrating models can be derived from existing models and relations?
- What properties can be modelled in an integrated model? What scope does such a model have?

The expansion of the analysis and the shown research questions will be matter of further research work.

3.2 Extending the use phase of complex mechatronic products

As stated in section 1, extending the use phase of products is one possibility to minimize the environmental impact of products. The approach proposed here is based on aspects of release management methods and Design for Maintainability and aims at extending the use phase of products by defining upgrades of features as a combination of software and hardware functionalities.

3.2.1 Background

When deploying new functionalities or changes into a running system, two aspects are crucial for the successful deployment: (1) the system should be upgradable with moderate effort, (2) the system integrity must be maintained. These aspects can be addressed by methodologies regarding Release Management and Design for Maintainability.

Release Management (RM) is originated from software development and describes the process and activities conducted to develop and deploy releases as a result of change requests. A major task of RM is to maintain the integrity and minimize the disruption of the original system during and after the deployment release of new features by prior planning and testing of the release (IEEE, 2013). A release in this context is a collection of "one or more changes to a service that are built, tested and deployed together" (IEEE, 2013). At the beginning of the RM process, a subset of changes (sometimes also referred to as requirements) is selected as the scope of the release (Carlshamre, 2002). Besides the development and implementation of the release, RM also covers the estimation of effort and the resource management needed for planning, design and implementation of releases (IEEE, 2013). In information technology, RM is well-established. The transfer to "hardware" products is still subject of research, cf. (Schuh and Eversheim, 2004; Schuh *et al.*, 2015).

Design for maintainability (DfM) comprises the consideration of aspects regarding for instance serviceability, reparability or supportability, minimizing the effort during the use phase of the system to keep it in or to restore it to a usable condition (Stapelberg, 2009). According to the IEEE Standard Glossary of Software Engineering Terminology, maintainability is defined as "the ease with which a software system or component can be modified to correct faults, improve performance or other attributes, or adapt to a changed environment" (IEEE, 1990). DfM is closely linked with the modularity of products whose foundation is laid during the early design phases in form of the product's architecture (Schuh *et al.*, 2015).

3.2.2 Problem statement & Approach

We propose an approach to consider the extension of product use phases during the design phase based on aspects of DfM and RM. This approach enables to increase customer benefit during the use phase and to estimate the effort required for lifting these by hardware upgrades or software updates.

Looking at the product's customer benefit over time, it is subject to exponential decay (cf. Figure 5a) and customers are likely to buy new, more beneficial, products before the actual physical end-of-life is reached (Umeda *et al.*, 2007), cf. Figure 5a. A crucial question derived from this fact is "How can the use phase be extended to match the possible technical life span of the product?". One possibility is raising the customer benefits during the use phase to decrease the customer's subjective sense of the need for a new product. One well-established procedure to raise customer benefit in software industry is to provide updates, adding new features with regard to current technologies. For software products, like operating systems or office software, it is a common procedure to provide updates of different kinds, e.g. security updates or service packs, during the products life time (Microsoft, 2016). The latter one may, however, add additional features to the software, which may increase the customer benefit. For highly integrated products combining hard- and software components, like smartphones, laptops, cars or mechatronic systems in general, if anything, only the software components get updated, but the hardware stays as it was. Thus, no maintenance procedures combining software updates and hardware upgrades are currently established in the industry. This leads to the fact that the full potential for extending the use phase of products (cf. Figure 5c) is not yet accessible with currently established maintenance procedures, cf. Figure 5b.

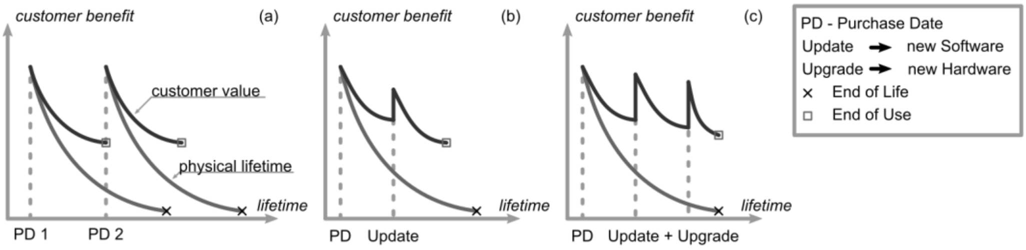

Figure 5: Customer benefit over product life times, in regard to software updates and hardware upgrades

To access this full potential, upgrades for the hardware of products are mandatory. The following example shall clarify the problem stated: As for a smartphone, there are regular updates adding new features and fixing bugs. Thus, from the software point of view, the smartphones customer benefit is raised again to a higher level with every update (cf. Figure 5b). Yet, for every update, more memory capacity is needed for the operating system. This leads to a reduction in the amount of memory that can be freely used by the costumer. Thus, the customer benefit level can never be as high as it was in the beginning, when the smartphone was initially purchased, because the customer renounces some of his usable amount of memory. This disadvantage could be balanced and the customer benefit could be raised to an even higher level (cf. Figure 5c), by providing hardware upgrades for elected parts of the smartphone, like memory or battery. Thus, by providing software updates und hardware upgrades, the use phase of the smartphone may even be extended up to the end-of-life resulting from failure of non-changeable parts.

For complex mechatronic systems like cars, the problem to solve is more complicated because new features, like driver assistance systems, are introduced with the next product generation (Albers *et al.*, 2016) and are a combination of specialized hard- and software components. Thus, to extend the use phase of the prior product generation, upgrades providing new features must be defined, regarding the available hard- and software components and their relations in the prior product generation as well as in the current product generation. For defining the scopes of these upgrades, a release management process can be used.

In summary, the basic idea as introduced before is to port one or more product features, like driver assistance systems of modern cars, from one product generation to a former one, cf. Figure 6.

As shown in Figure 6, two scenarios for porting are possible: (1) the porting can be realized by changing only software components, the existing hardware meets the requirements, (2) the porting can be realized by changing software components and upgrading or adding hardware components.

In both cases, a description of the feature, as a pattern persisting of required hardware and software components and their interrelations, is needed. This pattern may then be compared with the product architecture of former generations containing the existing hardware and software components. As a result of the comparison, the intersection between the former product generation and the feature pattern is determined. With this information, the necessary scenario for porting the feature can be chosen.

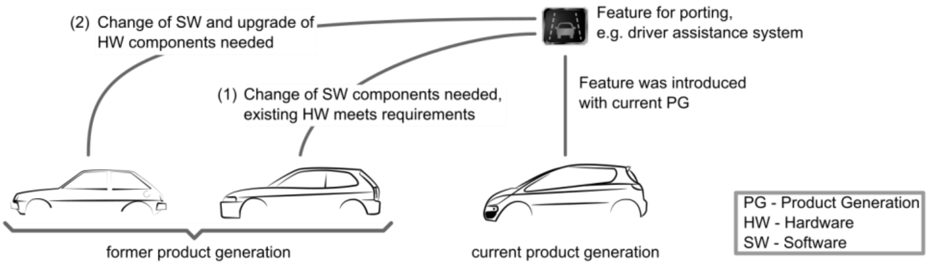

Figure 6: Transfer of features to former product generations and necessary

In further analysis steps, the effort for software changes or hardware development can be estimated. In the end, detailed information regarding the feature, the necessary scenario for porting and the estimated effort is available and can be used to make decisions on whether the development for porting the feature shall be executed. Of course, other information, such as business cases and profitability calculations, are needed for a decision. Gaining this information is, however, not part of the approach presented.
For the application of the approach, a model-based description of the product's architecture and the artifacts of the product generations based on the Systems Modeling Language (SysML) seem useful. By taking the prior remarks into consideration, the following research questions occur:

- What can an integrating modeling approach for modeling hard- and software functions and components and their relations regarding multiple product generations look like?
- How can the portability of features from one product generation to a former one be determined?
- How can the effort for development and implementation of those upgrades be determined?
- How can upgradability of mechatronic products in general be enhanced during the design phase?

Answering these research questions and further developing the approach introduced will be subject of further research.

4 CONCLUSION AND OUTLOOK

This contribution gives an overview of two planned research actions within life cycle development. Based on the general understanding of LCD by Umeda et al., it is detected that integrated modelling approaches are inevitable within development. Two concepts are proposed, addressing life cycle planning and the integration of upgradability during use phase. They share the basic hypothesis, that there is a lack of integrated modelling approaches, combining interests of different disciplines.
In further research, the first approach will be enhanced by expanding the analysis of existing modelling approaches in LCP and proposing options to combine them in order to harmonize the targets of the parties involved in planning. The second approach will lead to a model that integrates hardware and software modelling with the scope of extending customer benefit during use phase by upgrading. In order to proceed with the presented approaches, the stated research questions will be answered and further developed to provide integrated modelling approaches.

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