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Upgradeable Mechatronic Systems - An Approach to determine changing Product Properties using Foresight

Maximilian Kuebler*, Wolfgang Schuster, Stefan Eric Schwarz, Adrian Braumandl, Andreas Siebe, Albert Albers

IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany

* Corresponding author. Tel.: +49-721-608-47066; fax: +49-721-608-46051. *E-mail address:* maximilian.kuebler@kit.edu

Abstract

In light of the increasing complexity and dynamic of the market environment, there is a need to consider future requirements during the development of upcoming product generations. This applies in particular to modular product architectures as their elements are used in several products and over a longer period. To overcome this challenge and to develop more sustainable products, upgrading can be a solution. Based on identified options for action, this paper proposes an approach to determine changing product properties based on the Model of PGE – Product Generation Engineering. Depending on the potential of the individual characteristics of a product property in its future environment, the properties can be classified as static or dynamic time-dependent for later upgrade planning. The approach was applied in a case study and a research project. Its applicability and usability could be demonstrated. Results from the application of the approach can be used in development projects to define upgrade packages for the upcoming product generation or to optimize the modularization of future products.

Keywords: product development; design methods; upgradeable systems; life cycle engineering

1. Introduction

The product environment is subject to dynamic influencing factors that are generally outside the company's sphere of influence and cause uncertainty. These include changing customer requirements, markets, laws, social norms and values, competition, and continuous development of new technologies [1]. Therefore, the early stage of product development is characterized by a high degree of uncertainty, complexity, and leverage [2]. Product developers must take on a wide variety of challenges and problems to proceed successfully in the early stage. In this context, decisions made have a significant impact on the success of the product development process [3]. For example, due to incorrect decisions in the early stage, unplanned but necessary changes may occur. These changes are associated with high cost expenditures [4].

Upgradeable mechatronic systems can be a solution to the stated challenges. In order to minimize development efforts for new products, these mechatronic systems need modular product architectures. Despite inevitable changes in the product environment, the life cycle of a module should be as long as possible to make good use of its potential [5] and to enable sustainability [6]. Methods of foresight, such as scenario management, are already used in product development to reduce uncertainty. For this purpose, they are employed in various contexts including strategic business development or as a creative tool to support idea generation. However, in the context of upgradeable mechatronic systems, the question arises which modules implement product properties that are expected to change in the future and thus should be developed upgradeable. To answer this question, an approach that connects methods of foresight with product development on the

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level of technical principle and embodiment is needed. To enable long-term benefits and ease of implementation, the approach should build on the model of PGE – Product Generation Engineering. A three-step approach to determine changing product properties was developed to exploit this potential.

2. Research objective and methodology

As previously explained, there are several reasons to use methods of foresight in product development to determine changing product properties. The research objective of this paper is to develop an approach and demonstrate its applicability and benefits, which supports the determination of changing product properties. Therefore, three research questions (RQ) arise:

1. What are options for action based on existing literature?
2. What does an approach look like that determines changing product properties of modular product architectures over several product generations?
3. What are the benefits of the proposed approach in practice?

This paper is structured according to Blessing and Chakrabarti's Design Research Methodology (DRM) [7]. Each research question addresses a stage in the framework of DRM. Literature research on existing methods that use methods of foresight in the context of product development was conducted to answer RQ1. Research gaps and options for action were identified in the scientific discussion process. Following the options for action, two creative workshops with experts in integrated product development, PGE, and foresight resulted in a process model to determine changing product properties (RQ2). Lastly, the approach was applied twice: In a case study for its refinement and the project AgiloDrive2 to show the applicability and benefits of (RQ3).

3. State of research

3.1. PGE - Product Generation Engineering

During the early stage of the engineering process, product properties can be influenced and adapted with the least effort. However, there is a lack of knowledge about future properties, so uncertainty is high. This phenomenon is called the paradox of design [4]. PGE – Product Generation Engineering according to Albers provides solutions to overcome the paradox as methodical and model-based approaches [8]. This model of PGE can be used to describe the vast majority of development projects [8]. The authors state that the development of a new product never starts on a blank sheet of paper and specify the model of PGE with two main hypotheses [9].

The first hypothesis declares that the development of new products is almost invariably based on one or more existing products. The development of a new product thus becomes the development of a new product generation, with the underlying products being referred to as reference products. These reference products contain reference system elements that form the reference system [10]. Reference system elements can originate from a previous product generation, products from competitors, products from other industries, and even prototype solutions from research [10].

The second hypothesis states that the subsystems of the current product generation are developed from reference system elements via three variation operators [8]. These are the carryover variation, the attribute variation, and the principle variation. Carryover variation is the adoption of existing solutions from the reference system elements, whereby only adjustments at the interfaces of the system integration are made accordingly. Attribute variation involves the development of functional units by changing their attributes while retaining the solution principle. In the process of a principle variation, specific functional units are developed with a solution principle new to the development team [8].

In addition to its function as a description model, the model of PGE can also be used for risk assessment or to determine relevant validation scopes. The *PGE risk portfolio* combines attribute and principle variation as the *new development portion*, thus enabling an estimation of the risk for specific subsystems [11, 12]. Another possibility to deal with the need for more knowledge about future product properties is foresight, addressed in the following section.

3.2. Foresight in product engineering

Due to long product lifecycles and linked strategic decisions on the product architecture, knowledge about alternative future progressions can be a competitive advantage for companies [13]. The future is always coupled with change and cannot be precisely predicted. Foresight comprises all activities that help to identify possible future developments of complex and dynamic systems. It allows to gain knowledge on new market, business and product developments [14]. Within foresight, different methods are useful depending on context and the relevant time frame.

With an increasing time frame, the future gets less plannable as uncertainty increases [14]. Prognoses predict a future state or evolution of a system based on the current state and knowledge of the past evolution of a system [14]. The informative value of this method is thus limited to short time frames only. Trends are used in mid-term time frames. They denote possible progressions in the future that can be regarded as relevant for future business activities due to a high degree of probability [15]. For extended time frames, scenarios are developed to describe possible future environment, market, strategy and product progressions based on a complex system of influencing factors [16].

To develop scenarios, scenario-management according to Fink and Siebe is relevant to this paper [14]. The process consists of four phases to obtain various images of the future. First, the scenario field is systematically structured into different spheres described by influencing factors. Further, key factors are identified with the help of an influence analysis [13]. The second phase begins to look into the future. Future states are now systematically determined for each key factor and described as future projections. For this purpose, qualitative imaginable projections are primarily selected in scenario-management. These are fundamental development directions of a key factor that largely illuminate the possibility space. In addition, scenario-management assumes key factors as multidimensional [14]. In the third phase, the future projections of key factors are combined either bottom-up via a consistency analysis or top-down via a morphological box. The bottom-up approach examines how the different future projections fit together. Accordingly, whether they form a consistent scenario or not [14]. In contrast, the deductive top-down approach first considers which content-related topics can be identified. Subsequently, suitable projections are assigned to these topics [14]. The scenarios are formulated, focusing on distinguishing projections between the projection bundles. For communication, the scenarios are interpreted as descriptions, stories or other formats [14]. Lastly, the scenarios built are brought into a communicable format.

Scenarios can also be used in the innovation process to assess potential. Therefore, Fink and Siebe [14] propose the four-quadrant model of strategic innovation management. It matches scenarios with the organization in two different ways. External key factors, that cannot be controlled and controllable key factors. The four-quadrant-model connects environmental, customer, strategy, and product scenarios (see Fig. 3). It helps to assess business strategy, market potentials, product offering potentials, and future business opportunities.

3.3. Research gap

Different approaches in product engineering already use methods of foresight. The following section shortly summarizes the most relevant approaches in the context of this paper and describes the research gap to answer RQ1.

Fricke and Schulz [1] propose an approach called *Design for Changeability* which is a parallel process to product architecture development. Instead of avoiding changes during the product life cycle, the authors state that these changes are unavoidable in many environments to ensure the product's long-term success. They conclude that a product must be *changeable* and define the four aspects of changeability: Robustness, Adaptability, Flexibility, and Agility.

To increase the flexibility and agility of a product, upgrades are an option. Mörtl [6] proposes a process model for developing upgradeable products. The author mentions methods of foresight to anticipate future changes but does not elaborate further. Schiffer et al. [17] present a method that anticipates changes to develop one robust product architecture. Therefore, the uncertainty of customer properties using scenario-planning is assessed, and a detailed network analysis of the product's properties is conducted. Bauer et al. [18, 19] propose a four-phase method to support the development of change-robust platform architectures. The author also analyses the current product family and architecture. Instead of scenarios, a qualitative and a quantitative prognosis are used to determine the needed changeability of the platform. Further, Greve et al. [20] developed a *Feature Implementation Diagram*. With its help, product properties can be classified in terms of their implementation type as flexible or robust and their time horizon as immediate or providing. Therefore, an elaborate Conjoint-Analysis and Monte-Carlo-Simulation are used. Lastly, Marthaler et al. [21] propose a systematic approach for identifying product profiles with high innovation potential through foresight and a roadmap for prioritizing development scopes. For this purpose, the authors identify a product property's future customer relevance with the Kano model's help.

In summary, it can be said that different authors already connect methods of foresight with product development. Fig. 1 illustrates approaches linking the two areas based on [22].

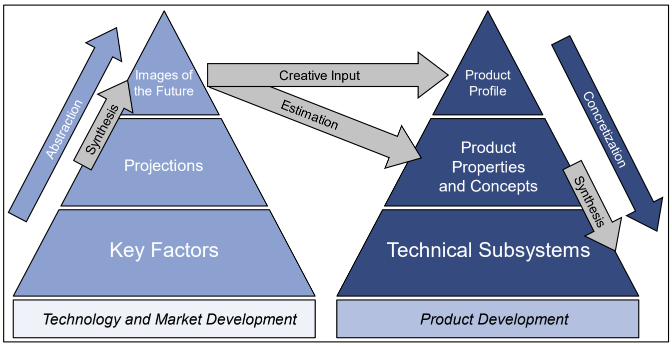

Fig.1. Approaches to connect technology and market development with product development based on [22]

On the side of technology and market development, with the help of foresight methods, an abstraction of the scenario field via key factors and projections to future images takes place. These scenarios are mainly used as creative input to develop product profiles or for ideation. The product profile is then concretized via product concepts and properties to technical embodiment, subsystems and the final product. Another approach is to estimate the future relevance of product properties for the customer with the help of scenarios. The presented method focuses on a different aspect: a way must be found to estimate *changes* in product properties in a time-efficient manner. An option for action is to transfer the knowledge about changing product properties down to technical subsystems. On this level, it can be used to adjust the modularization for changing properties or upgrades. Based on the repeated use of modules over a long period, the approach should be embedded in the model of PGE and require as little effort as possible. The corresponding approach developed in this work is presented in the next section.

3.4. Basic framework for the approach

The basis of the approach for determining changing product properties is understanding problems according to the considerations of Dörner [23]. Generally, the author defines a problem with two states. The undesired initial state and the desired target state, whose transformation is prevented by an obstacle at the time. In the framework of PGE, the current reference system describes the initial state and is transferred via the three variation operators into the target state.

4. Approach to determine changing product properties

In the context of the presented approach, there is an actual state with today's product properties and a target state that describes the uncertain future environments, customers, and products. By definition, a problem exists because it is not immediately known how the actual state can be transformed into the target state. Reference products represent the actual state according to the model of PGE, and the target state can be approximated by future images of the product, in this case, product scenarios. By executing a delta-analysis, changes and associated risks can be assessed. Fig. 2. shows the process model for determining changing product properties. The three phases State-Analysis, Target-Analysis, and Delta-Analysis, as well as their associated steps, are described below.

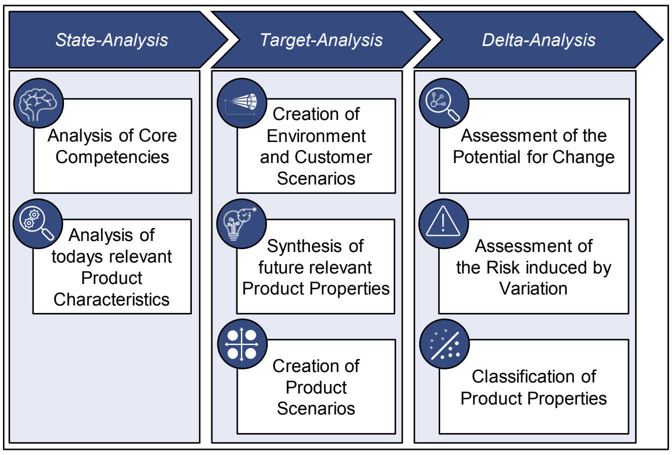

Fig. 2. Reference process model for determining changing product properties

In the *first phase* of the approach, the actual state is specified by analyzing reference products. The company's core competencies and today's product features are identified. The core competencies identified relate to product development and will be required later for scenario interpretation or the assessment of the risk induced by changes. The second step is the core of the State-Analysis and describes existing products or products currently under development. Therefore, the system of objectives of the development task must have already been determined. This system of objectives can be described in terms of PGE by reference system elements. The reference system elements can be specified from a property, functional or physical point of view. For the State-Analysis, the abstraction of the system under development at the property level is selected. Such an abstraction enables a solution-open product description and qualitative scenario building. In the context of this paper, a product characteristic is the manifestation of a product property. For example, *10 mm* is a product characteristic of the property *wall thickness*. By analyzing the elements of the reference system, product properties are derived. The result of this step is a catalog of today's product properties.

The *second phase* aims to systematically develop various future images of products, representing a possible target state in the future. For this purpose, the possible future environment of the products is described in the form of environment and customer scenarios. They are developed according to the method of scenario-management and serve as a starting point to derive future product properties creatively or systematically. Together with today's product properties, these form the initial product property catalog. The initial catalog usually consists of more properties of today than what is practical for scenario formulation. After performing a simple relevance evaluation, the final product property catalog consists of 10 to 15 properties. It is used to formulate product scenarios with a morphological box.

The *third phase*, the Delta-Analysis, aims to identify changing product characteristics and to generate knowledge about changes with high risk. It enables the classification of product properties into static or dynamic time-dependent. Fig. 3. illustrates the path through the four-quadrant-model during the first step, the assessment of the potential for change.

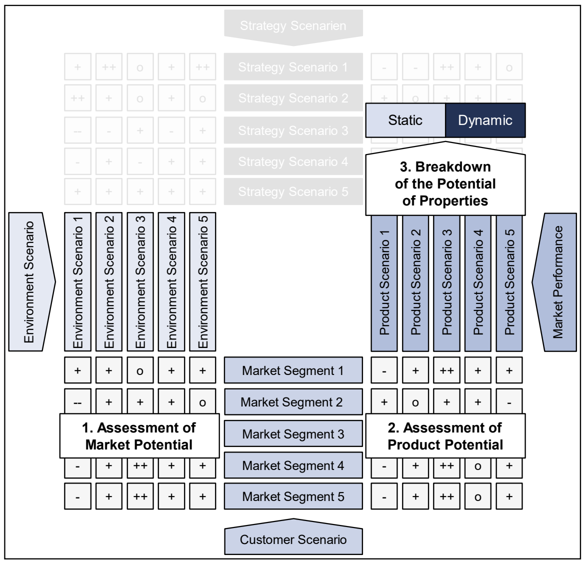

Fig. 3. Sub-steps for assessing the potential for change

The first sub-step comprises the assessment of the market potential and is located at the bottom left of the four-quadrant model. For this purpose, the market segments are evaluated in the environment scenarios. Environment scenarios describe the future development of the system of systems in which the product is embedded. Related spheres of influence describe the global and regional environment, including political, geopolitical, societal or scientific development paths. The assessment is carried out by answering the following question: Is the potential of a market segment in the respective environment increasing, decreasing, or neutral? The results evaluated can then be used to calculate the standardized mean value, which represents the weighting of a market segment according to its market potential in the future. During the second sub-step, the product potentials in the weighted market segments are assessed, analogous to sub-step one. Lastly, the potentials of the different product scenarios are broken down to the level of product characteristics with the help of a morphological box. The corresponding product potential is assigned for each product characteristic used in a scenario. By adding all potentials of a product characteristic from the different product scenarios, the potential of a product characteristic is obtained. This number should not be regarded as a probability of occurrence but as an *expectation afflicted with uncertainty*. From a qualitative point of view, static product properties have one product characteristic with high potential. Therefore, it can be expected to be a relevant product characteristic in the future. Quantitatively, this means that only one product characteristics potential is higher than the average potential over all characteristics of a property. On the other hand, dynamic product properties have more than one product characteristic with high potential. Consequently, the future of this property is unclear.

During the second step of Delta-Analysis, the risk induced by the variation of product characteristics is assessed. For this purpose, the PGE risk portfolio with its rating scale from one to nine is used. The rating depends on the degree of novelty, respectively the proportion of attribute and principle variation, as well as the origin of the knowledge about the reference system. The risk is low if the knowledge is present in the company and the degree of novelty is low. High risk is indicated if the degree of novelty is high and the knowledge about the reference system originates from another industry or outside the company. The risk of product properties is assessed by the mean risk value of the product characteristics.

Lastly, the results of the Delta-Analysis are summarized in a classification of product properties. It connects the knowledge about statics and dynamics with the risk induced by variation. Dynamic product properties with a high risk of variation entail a high change effort and should be prioritized as highly as possible during development. Dynamic product properties with low risk have a low change effort and can be adapted quickly. For static product properties, one property is dominant. A change in the future is likely not expected.

5. Application of the proposed approach

To answer RQ3, a case study to determine changing product properties of a coffee machine and the research project *AgiloDrive2* were conducted. The case study was built upon an already developed environment and customer scenarios to refine the approach after its creation. *AgiloDrive2* represents a research project developing a future-robust construction kit for electric traction motors. In the context of validating robustness, the developed approach was utilized. The following sections summarize the application of the approach in specific examples and its benefits for product development.

5.1. Case study

Because of the unchanged scenario-management process, the case study is based on existing scenarios on the future of the coffee machine market in 2030. Thus, the first two phases could be skipped and knowledge about the application during the Delta-Analysis was generated. It was found that the assessment for change is an easy and quick way to determine changing product properties. The two-step assessment process and subsequent breakdown of potentials reduce the risk of intentional or unintentional influence on the results of the approach. Seven product properties were identified as static and nine as dynamic. The properties filter, grinder, and design represent static properties while the milk foam unit, quality, and durability represent dynamic properties. Thereby, the procedure considers different possible developments for estimating changing product properties and makes the results available for the further planning of development scopes or product strategies. Therefore, it could be stated that applying the approach in *AgiloDrive2* is suitable.

5.2. Research project

For this application, environment, customer, and product scenarios had to be formulated. It was found that the formulation of three types of scenarios is time-consuming and requires a profound understanding of scenario-management. However, the three types of scenarios can be further used for early strategic detection, thinking ahead of development trajectories, or identifying future market segments or development scopes. After the Delta-Analysis, the resulting product potentials could be utilized to verify the configuration of the construction kit. Seven static and seven dynamic product properties were determined. E.g., it was found that synchronicity can be found as a static operating principle while the level of system integration and generation of the magnetic field remain dynamic product properties. Fig. 4. illustrates an extraction of the results in the shell model for the classification of statics and dynamics. The inside of the shell model shows the static properties. In contrast, the next shell shows the dynamic properties with several expected characteristics, and on the outside shell, dynamic properties with various equally expected characteristics are shown. With this visual tool, upgradable modules can be identified, or interfaces within modules adapted by linking product properties and functions. The knowledge about changing properties can be used for upgrading when the construction kit is further detailed.

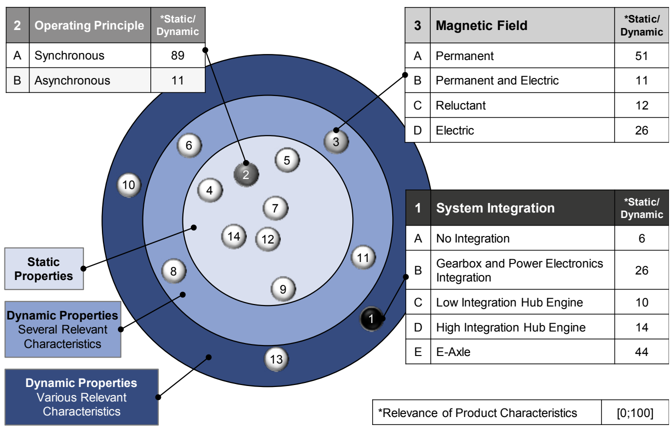

Fig. 4. Shell model for the classification of product properties

6. Summary and outlook

This article proposes an approach to connect methods of foresight with product development to determine changing product properties for upgrading. First, options for action, such as a time-efficient method to determine changing product properties, have been identified based on existing methods. Second, a reference process consisting of a State-Analysis, Target-Analysis, and Delta-Analysis has been introduced. The main result is the classification of product properties into static and dynamic time-dependent. Static product properties have only one product characteristic with high future potential. Therefore, it can be expected to be relevant in the future. Dynamic product properties have more than one product characteristic with a high potential, which is why no statement about the future can be made. Third, the process model has been successfully applied in a case study and the research project *AgiloDrive2*.

This contribution focused on the connection of scenarios with product properties. In the following research, the information about statics or dynamics of product properties needs to be abstracted down to the technical subsystems. Further, methodical support is needed to determine which technical subsystem or module should be upgraded and how it should be designed. Lastly, possibilities to reduce the time required for Target-Analysis should be explored.

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