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ROBUST PRODUCT DESIGN – INFLUENCING FACTORS ON UPGRADEABLE MODULAR PRODUCTS

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ABSTRACT

In today's VUCA-World it is necessary to consider future requirements to develop change- and future-robust future products, especially regarding the increasing demand for sustainable solutions. In order to address this situation, upgradeability of modular products can be a solution. Considering that elements of modular products are used in several different products and over a long period of time, there is a need to act on this challenge. To uncover areas with a need for action, a systematic literature review on upgradeable and modular products was conducted. After resolving four fields of action and under consideration of the need for sustainable products, another systematic literature review examined the solution space of upgradable modular product architecture. In conclusion, several influencing factors on the upgradeable design of modular products could be identified, which are presented in this work.

Keywords: Robust design, Upgradeability, Design for X (DfX), Sustainability

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1 INTRODUCTION

The accelerated development of new technologies and the trend towards individualization (ElMaraghy et al., 2013) and digitalization (Vogel and Hultin, 2018) lead to a shortening of technology and product life cycles. Along with the challenges of climate change, there is a call for new design methods in developing more sustainable products (Ceschin and Gaziulusoy, 2016). Upgradeability can be a solution to this. An supportive approach to reach the stated goal is modular product design (Schuh, 2010). With the help of multiple use of modules, not only can the amount of different modules be decreased in an efficient manner (Schuh et al., 2010), but their life cycles can also be extended through cross-generational use (Albers, Scherer et al., 2015). In order to enable late integration of modules , the resulting modular products must cope with future changes in the product environment so life cycles are as long as possible and to enable their sustainability (Greve et al., 2021); (Mörtl, 2003). The use of modules as a reference in several product generations creates a central challenge: cross-generational dependencies (Bursac, 2016). This effect gets intensified by over-the-air updates, which lead consequently to fast changes in hardware requirements. Software updates must be carried by the product architecture and, if necessary, supported by the replacement of physical components (Hansen, 2020). As a consequence, competitive future products will be characterized by the fact that they can cope with updates and upgrades efficiently on the hardware side as well (Düser, 2021). Therefore, the following article aims to provide an overview of fields of action for the future- and change-robust design of modular products and to identify factors influencing the interaction of upgrades.

2 STATE OF THE ART

As mentioned, modularity and future-orientation are trailblazers to upgradeable product design. Additionally, it is fundamental to build systematically on previous products and use knowledge of references in order to avoid errors that have been made and to leverage unused potential. In relation to this motivation, different research fields can be considered. First, modular product architecture, which represents the basis for flexible and thus robust products. Second, cross-generational dependencies through module-based product development can be described by means of the model of PGE - Product Generation Engineering. Thirdly, possible boundary conditions can be analysed through foresight. Lastly, design for X approaches can support in various contexts to employ upgradeable products.
According to Ulrich (1995) the product architecture can be described as the arrangement of functional elements, physical components and the specification of interfaces between interacting physical components. Unlike other construction methods such as differential or integral, the modular product architecture has strong connections within the components, while they are largely decoupled between the modules. Due to their physical separation, the individual modules can to a large extent be developed and exchanged independently of each other (Ulrich, 1995). Modular design is particularly important for hardware upgrades, as individual components can be replaced or added with little resource input during the products time-in-use (Khan and Wuest, 2018). This means that additional functions can be added to the product during the use phase (Krause et al., 2021). Through a product platform, individual requirements can also be considered through flexible components and costs can be saved due to the high degree of standardization. Product platforms are characterised by qualitative components and standardized, robust connections and are usually developed for several product families (Boorsma and C.A. Bakker, 2019). To implement this, different solution principles and several alternative technical implementations are required. In relation to the variety of the product portfolio, numerous references are generated during the product development process. The Model of PGE - Product Generation Engineering describes central aspects of the development of new technical products through the variation of these references, e.g. modules. The combination of references is called a reference system, which then consists of reference system elements (RSE). RSE represent company specific solutions or existing solutions of supplier or competitors, which determine a large part of the system architecture. The development of a new product generation results from the targeted combination of the activities of carryover variation (CV), embodiment variation (EV) and principal variation (PV). The combined quantity of EV and PV describe the amount of new functional units as new development share in the product generation (Albers, Bursac, Wintergerst, 2015). Related to the selection of suitable RSE is the aspect of customer centricity in the product development process. Early on, customer needs should be explicated in an efficient manner. One approach to model

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customer is in the product profile. The product profile describes a bundle of provider, customer and user needs in order to define the targeted benefits for later phases (Albers, Heimicke et al., 2018).

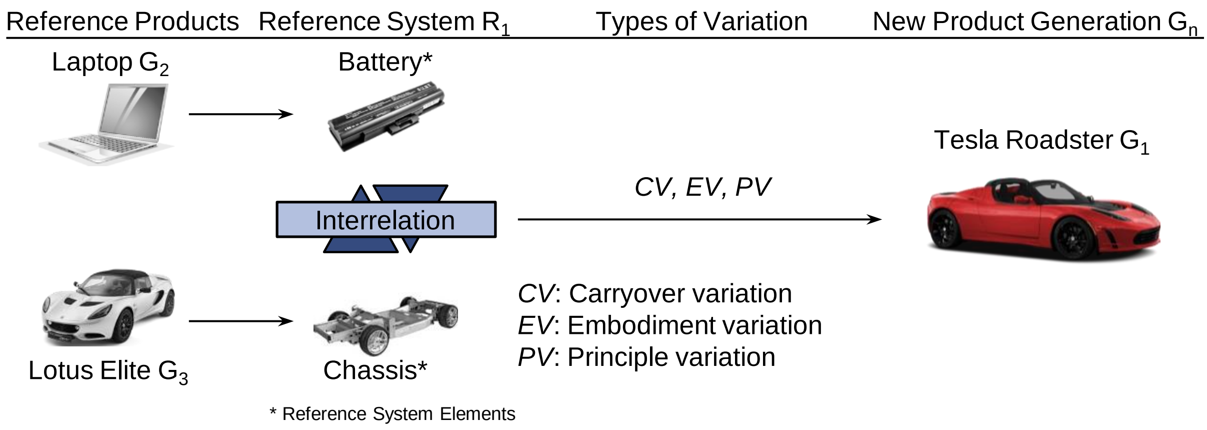

Figure 1: Simplified illustration of the model of PGE, based on Albers, Rapp et al. (2019)

An approach for early estimation of customer requirements is foresight. Which is why complex foresight during the product development stage is required for the integration of hardware upgrades so necessary adaptions through variation activities can strategically be applied. Methods of Foresight combine different approaches that help in identifying possible future developments of complex and dynamic systems. They provide knowledge on new market, business and product developments, although they just describe potential developments. Within foresight, different methods are useful depending on context and the relevant time frame. Prognoses address shorter time frames while trends can be used for foresight in mid-term time frames. Scenarios represent the most complex form of foresight and address extended time frames. The purpose of looking into the future is to obtain a clear picture of the future, to identify changes in the form of trends, and to recognize correlations between different factors and trends with the help of scenarios (Siebe, 2018). As a result, the so-called "early stage" has a high importance for the further process, since decisions on the design of the product architecture, technologies used and future requirements have a great leverage effect on the subsequent process (Albers et al., 2017). Through continuous validation and evaluation, future developments can be forecasted and already taken into account in the early stages of the planning phase (Marthaler et al., 2020). Internal design guidelines can be summarized under the concept of "Design for X". Design stands for certain activities in the development process that create a product and satisfy certain needs (Blessing and Chakrabarti, 2009). “X” describes different goals or requirements like changeability, flexibility or upgradability that are targeted in product development (Ponn and Lindemann, 2011). Product changes can be forced by new or not fully considered requirements. On the one hand, this is associated with additional use of resources; on the other hand, changes lead to a desire for higher product quality. Flexibility is referred to as a guideline in product development that enables changes in product design and performance (Ferguson et al., 2008). "Design for upgradeability" describes the general process of extending the useful life of the product through hardware or software upgrades during the use phase (Boorsma and C.A. Bakker, 2019).

3 AIM AND METHODOLOGY OF RESEARCH

3.1 Aim of research

Looking at this current state of research, it appears that the development of upgradeable mechatronic systems entails many opportunities, but no overview and interconnections of relevant and supportive approaches exists. Therefore, it is essential to generate a coherent understanding of their dependencies and boundaries and indicate potential fields of action for the generation of suitable development processes. Taken upgrading for development of change-robust products into account, it will be necessary to identify certain factors of influence for the adequate development support. This leads to the following research questions:

1. Which fields of action in future- and change-robust design of modular products can be identified from literature?
2. Which influencing factors on the integration of upgrades can be identified from literature?

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3.2 Methodology of research

In order to address these questions, a four-step research design was conducted (see Fig. 2). First, an explorative and systematic literature review was applied. The explorative literature review was conducted in order to prepare research fields of investigation, the right pre-defined search terms for the systematic literature review and to analyse interconnections between Foresight and the Model of PGE in Albers, Dumitrescu et al. (2018), an existing work containing a specific reference model based on Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009).

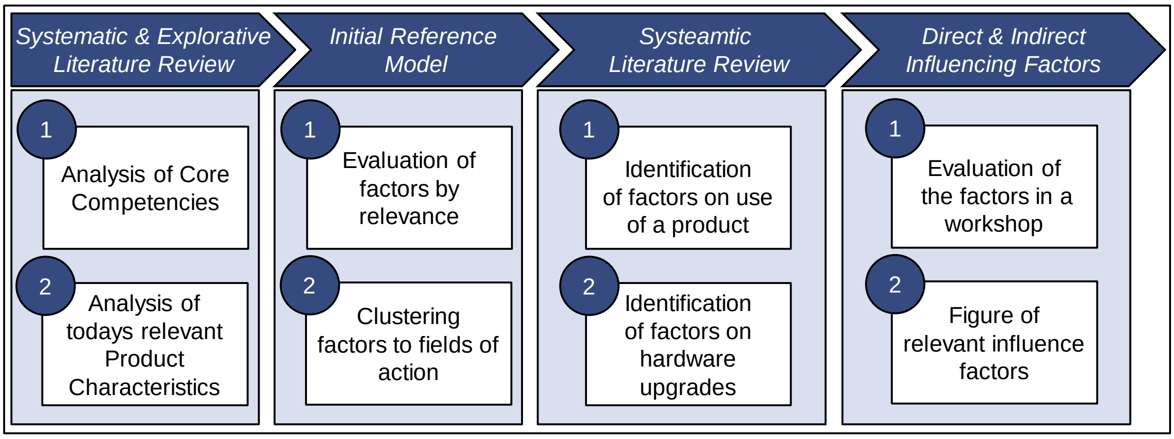

Figure 2: Methodology of research

The influencing factors according to Albers, Dumitrescu et al. (2018) were evaluated by the authors individually concerning relevance to future- and change-robust product design on a five-stage Likert-scale. Significant deviations in relevance were discussed in detail and as a result, 45 relevant factors were adopted. Furthermore, research fields of Foresight and Modular Produc Architecture were exploratorily investigated. Afterward, nine different search terms (German or English according to the database, see Fig. 3) were systematically applied in two databases (Google Scholar, Science Direct). The search terms were based on identic buzzwords but differed operators regarding the best application of the search engine. One search term addressed processes in building modular product architectures ("construction kit development", "modular kit development", "modular product development", "process" or "sequence"), one integration of product attributes ("modular design", "product characteristics") and one concerning future-robustness of modular product architectures ("modular design", "product development", "future robust", "upgradeability", "adaptability" or "customizability"). Of all search results, 113 publications were considered relevant after examination of the title, abstract, and detailed review (see Fig. 3), which led to 149 influencing factors. As a result, 194 influencing factors were sorted to form fields of action for the successful design of future- and change-robust products. To identify specific fields of action, all the factors identified were correlated with each other (Reference Model according to DRM). For this purpose, effect chains between these factors were built. In order to identify key factors, an active-passive grid was then drawn up and the resulting cores of key factors were identified. Cores of key factors represent influencing factors with a low active and a high passive and influence on at least six factors in three grades. Based on the length of different effect chains and their cores, four fields of action were synthesized. Third, influencing factors on upgrading were investigated in detail for further application. To determine the influencing factors, two systematic literature reviews in three databases (Scopus, Science Direct, and Google Scholar) were conducted. One literature review examined factors influencing the time-in-use of a product, using the search terms "product life cycle", "influence" and "product lifetime" while another literature review is composed of terms "Hardware-Upgrade" or "upgradability", "product", "product lifecycle", "product lifetime" to search factors influencing hardware upgrades. As in the previous systematic literature review, identic buzzwords were applied on all search engines, operators were customized. A total of 281 publications were identified in the first search and 271 in the second. The number of sources was then reduced in terms of duplications, the title, abstract, and content. In total 14 relevant publications were identified concerning the period of use and 11 publications in relation to the integration of hardware upgrades. Based on this, the relevant influencing factors were refined by an expert workshop evaluating the factors in terms of their influence on the integration of hardware upgrades. The factors were evaluated by considering no, indirect and direct influence on the implementation of upgrades in the product lifecycle by twelve experts.

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4 FIELDS OF ACTION

A comprehensive literature search was carried out to identify factors with regard to robust product design (see Fig. 3). Based on an explorative literature analysis, the topics process flow, product attributes and future robustness were chosen as central search points included in the literature review. A total of 28 of the identified factors fulfilled the requirement to influence more than six other factors over three grades. Taking into account the practical ability of the fields of action, additional five influencing factors concerning requirements for successful robust product design were considered. A thematical clustering of the 33 considered influencing factors led to four fields of action.

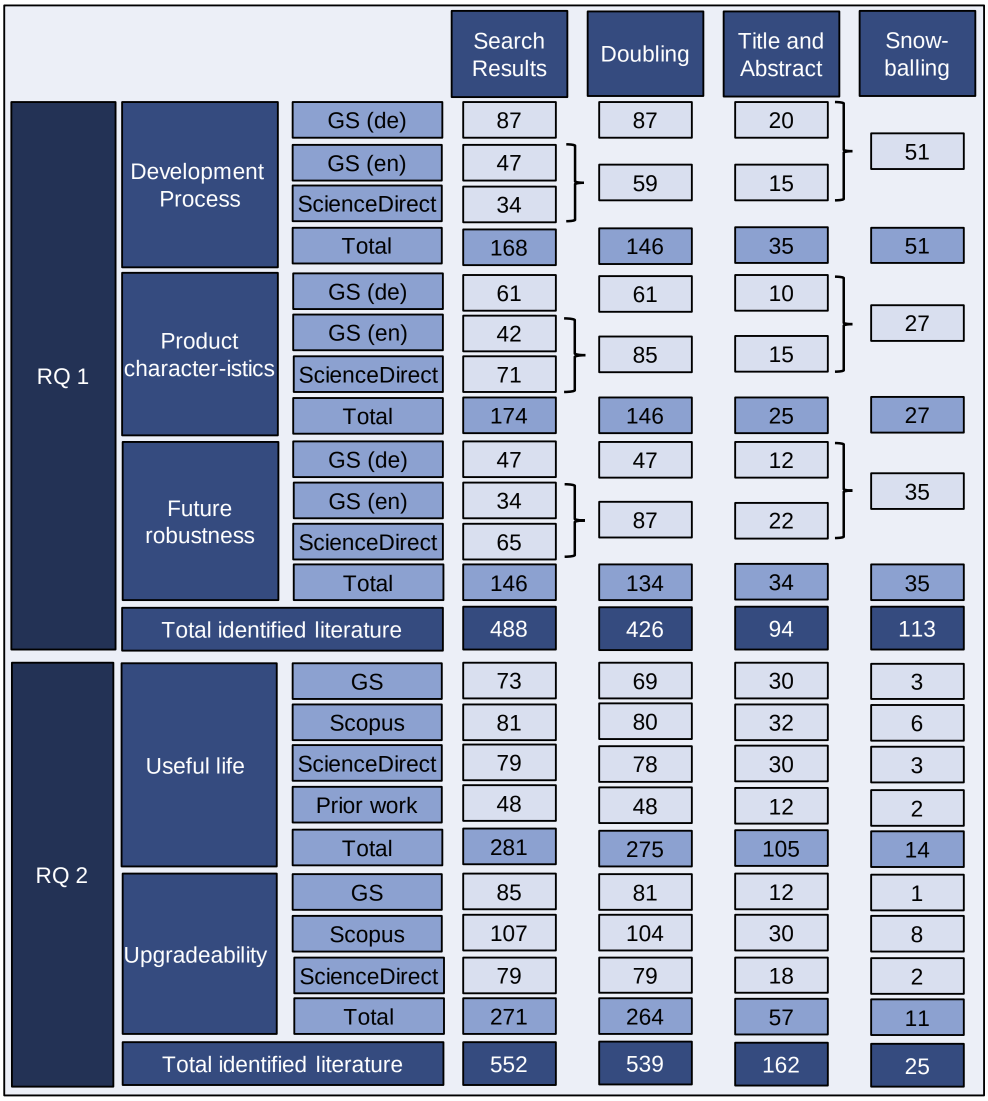

Figure 3: Systematic literature review investigating for fields of action and further investigation of upgradeability for robust design

4.1 Field of action 1: Designing upgradeable mechatronic systems

Upgrades of modular systems mean their extension by varying their function or performance. Upgradeability is important to fulfil evolving future customer needs. (Fricke and Schulz, 2005) The upgradeability of modular systems can be raised by a high degree of standardization of the interfaces of integrated modules.

4.2 Field of action 2: Using references in regard to the model of PGE - product generation engineering

In the model of PGE, products are developed based on reference systems like preceded modular products. Like this, knowledge management regarding future robustness is improved. (Albers,

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Marthaler, Walter et al., 2018) Choosing reference systems, the methodological evaluation of the future robustness of several options should be considered.

4.3 Field of action 3: Application of long-term foresight learning about future external boundary conditions

When developing future- and change-robust modular products, future requirements derived from future boundary conditions need to be considered. (Greve et al., 2021) Future boundary conditions can be concluded by applying long-term forecast methods like scenarios (Fink and Siebe, 2016). Especially the application of customer scenarios is important in modular product architecture development. (Greve et al., 2021) The information from a scenario-analysis in Early Stages of product development can be applied in many ways raising future robustness of developed systems. (Marthaler 2021)

4.4 Field of action 4: Conception of the modular product architecture being suitable to user-centred requirements

Concepting the future robust modular architecture, future requirements conducted by a scenario analysis must be considered. Future requirements can be determined by talking to suppliers of modules, materials, and technology as well. (Greve et al., 2021) According to Renner (2007), future requirements can be synthesized by so-called modular kit scenarios describing possible alternative configurations of the modular product architecture. Alternatively, Greve et al. (2021) suggest a method considering the variety of required products based on a customer-scenario analysis concerning today's product portfolio. The elaborated results are then considered for implications in the design process. Especially requirements originating from customers and users need to be methodically implemented in future products regarding future- and change-robustness. (Marthaler 2021)

5 INFLUENCING FACTORS IN DESIGNING UPGRADEABLE MECHATRONIC SYSTEMS

As mentioned in the beginning, modular product architecture, PGE, Foresight and Design for X offer potential for robust product design. Through their interactions and overlaps in the form of the derived four fields of action (see Section 4), it is important to identify levers for enabling the associated methods of robust product design. Only on the basis of these can a target-oriented support for development processes be elaborated. The following literature research serves this purpose. In order to ensure the robustness of the products developed through subsequent support, the field of upgradeable mechatronic systems was investigated in a first search, as well as the influences on the resulting product during its use in a second search (see Fig. 3). A total of 134 factors were identified in the first systematic literature review, and 81 factors were identified in the second. These factors were then reduced according to duplication and relevance, resulting in 18 factors in the first search and 23 factors in the second search.
The factors were then consolidated and combined into 27 final influential factors.

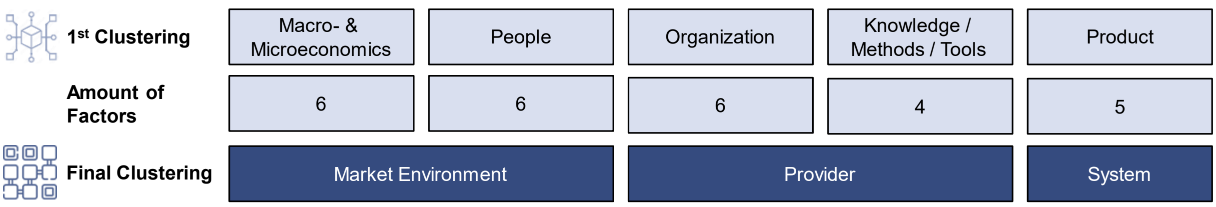

Figure 5: Clustering of influencing factors

The factors were assigned to the following categories according to Design Research Methodology (Blessing and Chakrabarti, 2009): Macroeconomics, Microeconomics, Organization, Knowledge/ Methods/ Tools, People, and Product (see Fig. 4). During an expert workshop, the 27 influencing factors could be categorized into 10 factors with indirect influence and 17 factors with direct influence on the integration of hardware upgrades. In the workshop, the factors were further analysed according to relevance. Twelve scientists with several years of professional experience in the field of mechanical engineering and product development were interviewed during a workshop at Karlsruhe Institute for Technology. The final figure (see Fig. 5) is divided into different system levels and was developed

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following the Scenario development according to Fink and Siebe (2016). In the figure ten success-relevant influencing factors with direct influence are shown and explained in relation to the market environment, the provider, and the system.

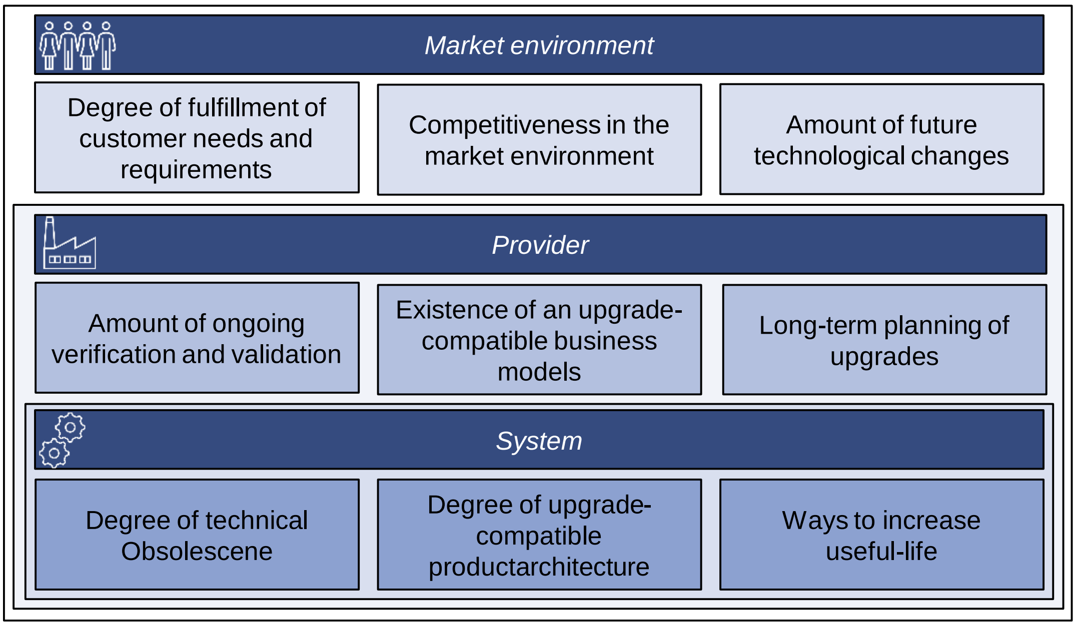

Figure 6: Influencing factors in designing upgradable mechatronic systems

5.1 Market environment

The market environment includes customers and competitors as well as general structures and topics such as political, social, economic, ecological, and technical factors are included.

5.1.1 Fulfilment of customer needs and requirements

Customer satisfaction is linked to various requirements. On the one hand, the integration of hardware upgrades can create new enthusiasm requirements during the usage phase, and on the other hand, changing customer requirements can be considered (M. Inoue et al., 2014). Furthermore, individual user adaptations and individual customer segments are playing an increasingly important role for companies. Modular products are characterized by a high degree of individualization (Agrawal et al., 2016).

5.1.2 Competitiveness in the market environment

The market environment is composed of various players, such as suppliers and sellers, direct competitors, or the secondary market, such as eBay. Hardware-upgrades and longer product useful life can lead to a lower sales volume and accordingly, the competitive pressure for the company increases (Agrawal et al., 2016). In addition, other companies can offer hardware-upgrades, which on the one hand can create new markets, and on the other hand can create competitors for own upgrades.

5.1.3 Amount of future technological change

Rapid technological change can make products technically and emotionally obsolete as alternative products with additional and better features become available. Customers replace their existing product for a new alternative and the product useful life shortens (Agrawal et al., 2016; Khan et al., 2018).

5.2 Provider

Internal structures and stakeholders such as decision-makers in the various development and production phases are summarised in the provider cluster. Also considered are models, design principles ("Design for X") and methods for product development.

5.2.1 Existence of an upgrade-compatible business model

New and adapted business models are required to integrate hardware upgrades, as sales volume will decrease with longer product life. Customer-oriented service models, warranties (Ulku et al., 2011)

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and product leasing models with ongoing upgrade plans (Chierici and Copani, 2016) are possible approaches for business models. Furthermore, initial product prices should be kept low and later upgrade prices should be set higher (Ulku et al., 2011) and upgrade constraints should be kept as low as possible.

5.2.2 Scope of ongoing verification and validation of requirements

To address customer needs, new international standards, and technological trends, ongoing verification, and validation of requirements during the use phase is important (Khan and Wuest, 2018).

5.2.3 Long-term orientation and planning of upgrades

For sustainable integration of hardware upgrades, the organization is encouraged to establish a long-term upgrade plan and communicate it accordingly with customers (Pialot et al., 2017). Forecasts of future technology trends and customer requirements, as well as the time and financial framework for future product upgrades, should be established as part of the development phase (Umeda et al., 2005).

5.2.4 Degree of methodological support for planning upgrades

Hardware upgrades can be embedded in various models and methods for product development in the context of PGE and on the other hand, be supported by so-called "roadmaps". A "roadmap" considers all important aspects from product development to market launch. Furthermore, it embeds the planning of upgrades during the use phase and serves as a guide for ongoing upgrades (Boorsma and C.A. Bakker, 2019)

5.3 System

In addition to the supplier, internal product-specific factors are summarised in the cluster system. The technical implementation to extend the useful life and integration of hardware upgrades is the focus here.

5.3.1 Technical, environmental and economic durability

Technical product aging is largely due to material durability, wear and tear, or functional durability. At the same time, user behaviour and the handling of the product conditioned by warranties, social values or repair costs play a role. As a result of product aging, performance is reduced and the service life is shortened as the customer switches to other products (Bobba et al., 2016). Modular product architecture can also lead to performance limitations due to additional interfaces or additional weight (Agrawal et al., 2016).

5.3.2 Degree of upgrade-compatible product design

A modular product architecture or platform strategy is of great importance for the integration of hardware-upgrades. Furthermore, a flexible design plays an important role in order to be able to react to changing requirements and new customer needs (Khan and Wuest, 2018). Product design, determined by product type, is another key influencing factor. "Contemporary products," are fast-moving, defined with technological advancements, and thus offer great opportunities for upgrades. "Technical workhorses" are characterized by a constant, reliable range of functions and long product life. "Investment products" are costly to the customer compared to other products and the customer usually builds a special bond with the product (Cox et al., 2013). Hardware-upgrades can serve to create new emotional incentives for the customer during the usage phase in order to strengthen the emotional bond.

5.3.3 Ways to increase useful life

To integrate hardware-upgrades, overall product life is important. Preventive and predictive maintenance measures or appropriate repair measures in case of wear and tear or other faults can increase the useful life. Remanufacturing through upgrades offers another way to increase the lifetime in general (Khan et al., 2018).

6 CONCLUSION AND OUTLOOK

In this work, four fields of action on robust product design and 17 direct influencing factors on integration of upgrades were concluded. The four fields of action indicate not only potential use and interconnections of the stated research fields for robust product design, but employ the development of engineering processes above identified specialist approaches on unique problems. To employ the fields of action, a new engineering process will be developed based on the influencing factors while using the motivation of the synthesized fields of action: Methodological integration of user-centred requirements identified using foresight and design of upgradeable mechatronic systems based on the model of PGE. Other relevant sources may have been excluded by restricting the search strings and thus the picture of literature considered may not be complete. Additionally, to raise validity of the fields of action, further studies which take practical applications into account need to be conducted and the fields of action and the influencing factors need to be unified. To what extent the identified fields of action and influencing factors can be confirmed and correlate to each other, further be profitably used in a robust product design approach is part of future research.

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