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Concept for Product Architecture Evolution Planning in the Context of Circular Economy

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Abstract

The linear economic model of the manufacturing industry requires a fundamental shift towards a circular economy. The extension of product lifespans through value-adding upgrades serves to conserve resources and promote sustainability. However, the product architecture may constrain the potential for value enhancements through product upgrades. This necessitates the evaluation of whether novel features can still be integrated into the existing product architecture rather than a new product generation. A conceptual framework is employed to facilitate decision-making in the evolution planning of circular product architectures, which weighs the upgrade's development and reassembly effort against its added-value and the architecture's future viability.

Keywords: Ciruclar Economy, Product Upgrade, Product Architecture, Continous Innovation

1. Introduction

There is a global need for solutions to cope with the growing competitive and innovative pressure on manufacturing companies and the increasing challenges of the sustainability transition [1]. The circular economy emerges as a promising solution to these challenges, offering an approach that not only enhances resource efficiency but also promotes value creation through sustainable practices. Contrary to traditional end-of-life concepts, the circular economy describes a deliberate and targeted industrial system that emphasizes recovery and renewal [2]. By rethinking traditional linear models of production, industries can leverage circular principles to enhance their processes, innovate their products, reduce waste, and ultimately achieve a competitive edge in an environmentally conscious market [3].

A critical aspect of this transition involves the lifespan extension of technical products. The extension of the product's life time can be achieved through various measures such as repairs, refurbishment or remanufacturing [4]. Given the extended period of product usage, it is necessary for manufacturers to ensure that their products remain attractive and offer continued value to consumers [5]. Thereby the implementation of value-enhancing product upgrades is of significant importance with regard to the objective of enhancing customer satisfaction and reducing product obsolescence. In addition, the longer lifespan of technical products can reduce the consumption of resources and increase the profitability of products [6]. This necessitates a strategic approach to product lifecycle management that addresses both current functionality and future adaptability. By prioritizing longevity through modularity, businesses can integrate innovations, while

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significantly reducing resource consumption and promoting sustainability.

However, the integration of product upgrades in a existent product architecture generation over extended periods presents a great challenge for manufacturing companies. Upgrading existing products without altering their architectural framework leads to diminishing degrees of freedom in implementing necessary technical changes and additional features [7]. In this regard, the evaluation of the viability and potential impact of product upgrades on a given product architecture generation represents a central question.

Therefore, there is a need for a systematic approach to product architecture evolution planning within the context of the circular economy. This paper aims to derive a conceptual framework for this approach, determining whether the technical change of an existing product is still feasible in regard to its product architecture. Therefore, the fundamentals of product architecture in chapter two. Chapter three presents existing approaches from the literature that are related to the objectives of the paper. Based on the theoretical deficit, a framework for product architecture evolution planning is presented in chapter four.

2. Fundamentals of product architecture and upgrade planning

Value-enhancing circular economy forms the basis for the implementation of product upgrades. To upgrade a product, the upgrade must be possible within its product architecture. Thus, the key aspects of the value-enhancing circular economy and product architecture are described in the following sections.

2.1. Value-enhancing circular economy

The circular economy can be described as a model for economic growth that reduces waste and pollution by preserving the value of products and materials, ensuring they remain in continuous circulation [8]. Enhancing the value of products by extending their functionality through upgrades instead of simply maintaining their functionality as well as keeping them on the market for further life cycles is called value-enhancing circular economy, commonly referred to as upgrade circular economy [9].

Upgradability is therefore a key factor in achieving value-enhancing circular products and is considered an element of the circular economy [6]. In order to achieve the required longer life cycles and value enhancement in the usage phase of circular products, it is essential to ensure that new functionalities and their underlying technologies can be introduced into the product after initial production and during or between two use cycles [4]. Replacing just 10-30% of the components makes a complex product almost equivalent to a new product and thus enables savings of up to 50% in resources and emissions [10].

The transformation towards a circular economy requires an understanding of the market changes and the respective customers as well as anticipated technological leaps for future product upgrades. These perspectives can be used to develop a product architecture for circular products [4]. Further explanations about characteristics and structure of a product architecture follow in the next section.

2.2. Product architecture

The product architecture is defined as the quantity of all elements and their relationships that are required for the design of the products based on them in terms of their geometric, technological or functional design. This product architecture is structured hierarchically and divided into functional structure and product structure [11]. Fig. 1 depicts exemplary this modular and two-part product architecture.

The functional structure represents the function of the product which is parted into subfunctions. It describes a product solution independent and its requirements from the customer's perspective. In comparison, the product structure depicts the structured composition of the product through its modules and components. The product structure's aim is to structure the product, describe the relationship between components and to increase the multiple use of assemblies and components [11].

Further both structures are characterized by their formulation across product portfolios and lifecycles. Usually, they are developed at the same time, which is why the process must be an iterative process to determine the transformation relationships with multiple change of views in order to obtain an optimal architecture result [11].

Transformation relationships describe the connection between the functional structure and the product structure. They are defined by the degree of independence between subfunctions and the respective components, which realize the function. On the one hand, a functional independence describes the autonomy of individual functions. On the other hand, there is physical independence, which represents the physical separability of components. Different types of modularity arise depending on the degree of independencies [12]. In this course, integral and modular architectures can be distinguished.

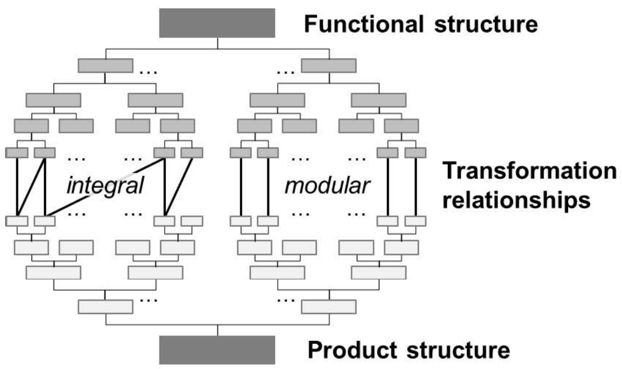

Fig. 1. The product architecture is composed of the functional and product structure with respective transformation relationships

Integral product architectures are characterised by a high number of dependencies of transformation relationships between functions and components. The integrity is excellent for developing high-performance products through component optimization. While a high degree of independence of the functions from components through direct transformation relationships between a function and an individual component represents a modular product architecture, it makes it easy to disassemble and replace components. This leads to the trade-off between integral architectures, which interconnections make disassembly and replacement of components challenging, and modular architectures, hindering high levels of design optimization. As a result, upgradable products need to achieve a product architecture suited for value enhancements, while still considering modular assembly [7].

3. Related Work

The following section examines related scientific work regarding product architecture evolution planning. Five relevant approaches in the context of this paper are briefly presented and evaluated in terms of their suitability for planning product architecture generations in the circular economy.

The study of [6] examines the concept of upgradability as a strategy to extend product lifetimes, with a particular focus on product service systems. The authors argue that a reduction in product lifespan has a considerable impact on both the environment and the economy, resulting in increased waste and resource depletion. The authors link the definition of product upgradeability directly to the products architecture. However, the product architecture is not considered further by the authors in the assessment of upgradeability. Despite its potential benefits, such as reducing environmental impact and enhancing economic value, the study highlights that practical applications of upgradability remain limited and require further empirical research to validate theoretical frameworks.

In their paper [13] put forth a methodology for designing upgradeable products through effective upgrade planning. The authors derive a systematic methodology for upgrade planning, which encompasses the selection of a target product in the first step, followed by the construction a database of components, including cost, performance, and market timing in the second step. The third step compromises the alignment of user demands with the product structure. Subsequently, design solutions are determined based on user demand patterns. Finally, the evaluation of product upgrades is conducted as a crucial step of the product development process, assessing multiple design solutions over the entire product lifecycle. The proposed methodology is designed to facilitate the creation of upgrade plans that can accommodate future user demands. However, the theoretical framework provides only a superficial overview of the required steps and indicates no specific methodical approach for achieving the objectives. In particular, the methodology refrains from the assessment whether upgrades can be integrated into the existing product and the foreshadowing of technological leaps.

[14] address the challenges of planning product upgrades in mechatronic and electronic products due to rapid technological changes and customer demands. A structured process for strategic release planning that includes defining a release strategy, structuring a release plan, and selecting features based on value, urgency, and given restrictions is presented. The methodology enhances decision-making by integrating various value aspects, aiming for long-term product success and adaptability across different domains. By integrating various aspects such as customer value, market competition, economic viability, costs, feasibility, and risks into the decision-making process, it aims to enhance long-term product success while ensuring adaptability across different domains. Although the methodology offers a comprehensive account of upgrade release planning, it does not address the feasibility or future viability assessment of the product architecture.

[15] present a framework for product developers to determine the optimal lifespan of products, considering three perspectives: the user, the business, and resource efficiency. The paper addresses the concept of product durability within the context of a circular economy, emphasizing its importance in facilitating the transition towards more sustainable practices. It emphasizes that efforts to extend product lifespan should be context-specific, rather than solely focused on longevity. Although the approach offers methodological support for selecting one of the life cycle maintenance strategies, it does not address the specific requirements for planning product architecture generations and assessing the upgrade’s feasibility.

A decision-support method is proposed by [7], which integrates product architecture selection with upgrade cycle planning. The evaluation of integral and modular architectures is based on three key criteria: environmental load, cost, and customer satisfaction. The methodology entails the development of evaluation models, resulting in the formulation of a comprehensive evaluation index, designated as the upgradable architecture index. The index is designed to assist in the selection of the optimal combination of architecture and upgrade cycle. The methodology developed offers a framework for decision-making in product architecture design, with the objective of incorporating later upgrade cycles into the initial conceptualization phase. Nevertheless, the actual implementation of the upgrade and potential technological disruptions within the product architecture are not considered.

In conclusion, the approaches presented emphasize the necessity of planning upgrades for products with modular product architecture, demonstrating a range of possibilities, from upgrade strategies to concrete decision support. Thereby, the added value and costs of the proposed upgrade need to be considered. However, the existing approaches reveal certain shortcomings with respect to the associated planning of product architecture generations. Firstly, the backward compatibility of the upgrade is not considered by assessing the implementation effort required for the integration into the existing product architecture. Secondly, no approach provides an assessment of the future viability of the product architecture itself, considering anticipated technological advancements.

4. Results

The concept for a systematic approach to product architecture evolution planning within the context of the circular economy is based on five steps. The first step involves characterizing the technical product changes in the form of an upgrade. This is followed by an evaluation of the respective upgrade in terms of the realization effort, the expected benefits and the future viability of the product architecture. Finally, the three evaluation dimensions are combined in order to derive recommendations for the planning of product architecture generations.

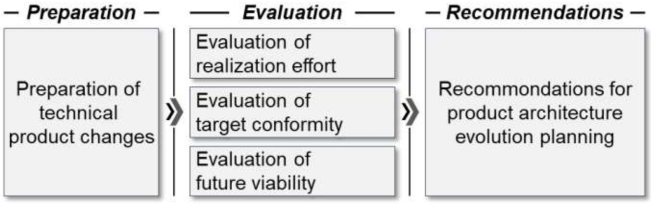

Fig. 2. Overview of the concept for product architecture evolution planning

4.1. Deduction of reference cases of technical product changes

The first step of the conceptual framework entails the description of technical modifications to existing products within the context of a circular economy. This description includes the identification of superordinate reference cases of technical changes. Subsequently, the product changes are characterized in accordance with a specific reference case.

Initially, the characteristics of technical changes in the circular economy are identified. On the one hand, triggers of technical changes are included and, on the other hand, characteristics for describing the change cases are distinguished. When describing triggers of change, a distinction can be made between internal and external factors [16]. Internal triggers of change usually include company-specific goals, such as increasing efficiency or reducing costs. In contrast, external triggers of change represent global factors that affect all companies in the competitive environment in the form of changes in regulatory requirements, market and customer conditions, or technological advances. Furthermore, the identification of features and their characteristics is required to describe the technical changes.

In the second part, reference cases of technical changes in the circular economy are identified and selected. Due to the diversity of technical product changes, it is important to identify superordinate reference cases that can be used for the subsequent evaluation of product upgrades. By assigning product upgrades to these reference cases, not only comparability of multiple changes is ensured, but also the evaluation is simplified, since only relevant aspects depending on the reference case must be considered.

The identification of reference cases for product modifications in the circular economy is based on the characteristics of the Kano-Model [17]. Accordingly, product features can be categorized as excitement, performance, and basic features. Excitement features positively surprise customers and lead to high satisfaction when they are present, while their absence does not cause dissatisfaction. Performance features influence customer satisfaction in direct proportion; the better they are fulfilled; the more satisfied customers are. Basic features represent fundamental requirements to ensure customer satisfaction; their non-fulfillment leads to dissatisfaction, but their fulfillment does not significantly improve satisfaction. The transfer of the features of the Kano-Model to technical product changes in the circular economy results in three reference cases: the function integration, the function improvement and the function guarantee, as shown in figure 3.

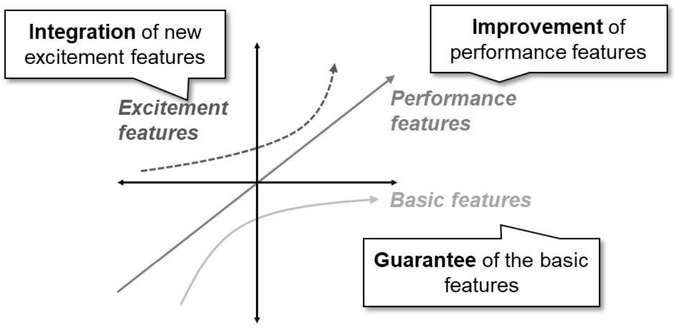

Fig. 3. Reference cases for technical product changes in the circular economy

The functional integration is the counterpart to excitement features, in that the customer is offered new functions for his existing product. Analogous to performance features, functional improvements increase customer satisfaction by raising existing performances. Finally, the functional guarantee ensures the basic requirement for the continued usability of the product without offering the customer any added value.

The reference cases serve as a prerequisite for the subsequent evaluation of technical changes for planning product architecture generations.

4.2. Determination of the realization effort for technical product changes

In the second step of the concept, the first of the three evaluation dimensions is evaluated. The aim is to assess the realization effort of the technical change. The realization effort consists of the development effort for the change itself and the integration effort for the change into the existing product.

To determine the realization effort, the scope of the change is first defined. The scope of the change describes the range of the change effects on affected components and software parts. The product structure, which hierarchically represents the links between components, is suitable for analyzing the change effects on components. The software effects can be analyzed with the help of dependency diagrams to identify interfaces between software systems and components [18]. Based on the scope of the change and the characterization of the reference cases from chapter 4.1, the changes can be assigned to a unique type, which is used for the subsequent effort assessment.

The realization effort is determined based on criteria such as complexity, interfaces, required resources and costs, which quantify the development and integration effort of the technical change. The identified criteria are then evaluated in terms of their relevance to the reference cases, as different criteria must be considered for a function guarantee than for a function integration. In the latter case, technical changes are subject to a significantly higher level of complexity and the risk of development is more severe. By evaluating the relevance for each reference case, the criteria for evaluating the realization effort can be weighed against each other.

Then, the development and integration effort are evaluated based on the weighted criteria for the specific type of reference case. The evaluation is based on key figures of the respective evaluation criteria. The weighted average of all evaluated criteria represents the realization effort of the technical change, to be considered in the planning of product architecture generations.

4.3. Evaluation of the target conformity of technical changes

In the next step of the methodology, the benefit of the technical product change is evaluated. To determine the benefit, the conformity with the company's individual goals for the value enhancing circular economy are considered.

To determine the required target system, target fields of product development in the context of the circular economy, such as competitiveness, sustainability or innovation management are identified. These can be identified via a bibliometric analysis, which allows for a structured analysis of large volumes of literature in which overarching relationships between articles and temporal trends can be identified [19]. Company-specific goals are then assigned to the target fields. Thus, overarching and sector-specific goals must be taken into account. For each goal, criteria are defined to measure the quality of goal achievement and corresponding key figures are selected. Finally, the target fields can be weighted against each other to prioritize the target system within the company.

Once the target system has been derived, the target conformity of the technical change can be determined. This determines the extent to which the technical changes meet the respective targets. The evaluation is carried out on a Likert scale between low target conformity and high target conformity [20]. The weighted sum of the target conformity gives the total value of the benefit of the technical change for the planning of the product architecture generations.

4.4. Assessment of the future viability of the product architecture

The last evaluation dimension is dedicated to the determination of the future viability of the product architecture itself. The aim of the evaluation is to assess the extent to which the existing product architecture can be adapted to future requirements and thus independent of individual changes. The adaptability of the product architecture is a crucial aspect of product architecture planning.

For this purpose, relevant future product technologies can be identified with the technology radar methodology [21]. In order to evaluate the importance of these product technologies, possible projections of future scenarios can be derived on the basis of model-based scenario techniques [22]. Four steps are essential to anticipate future scenarios. In the first step, areas of influence on technology development are identified and described by corresponding influencing factors. Possible projections are assigned to the influencing factors, which represent possible future developments of the influencing factor. In the second step, the effects between the influencing factors are analyzed. In doing so, factors are identified that actively affect other influencing factors. Consequently, these are key factors that significantly influence future technology scenarios. In the third step, a consistency analysis of the projections of the key factors is carried out. Based on the consistency analysis, the projection combinations with the highest consistency can be identified. These projection combinations are the scenarios to be considered, which are described in the fourth step.

Based on the scenario descriptions, the relevance of the identified technologies through the technology radar can be assessed for each scenario. This enables the evaluation of the integrability of the most relevant future technologies into the product architecture. The objective of this is to determine the technology commonality of the product architecture. Thus, the elements of the product and function structure affected by the technology are identified. Subsequently, an assessment of the feasibility of the technology scenario is carried out based on the number of potentially affected functions and components and the modularity of the product architecture.

The technology commonality of the product architecture is composed of the ratio of realizable technology scenarios to the totality of anticipated scenarios. The technology commonality should provide an indication of the future viability of the product architecture for the planning of product architecture generations.

4.5. Derivation of recommendations for action for product architecture evolution planning

The final step of the methodical concept includes the derivation of recommendations for planning product architecture generations. In the course of this, the previously presented evaluation dimensions are used to determine the extent to which product upgrades can be implemented on the existing product architecture or whether there is a need for a new product architecture generation.

To derive the recommendations for action, clusters of the corresponding evaluation dimensions realization effort, target conformity and future viability are formed first.

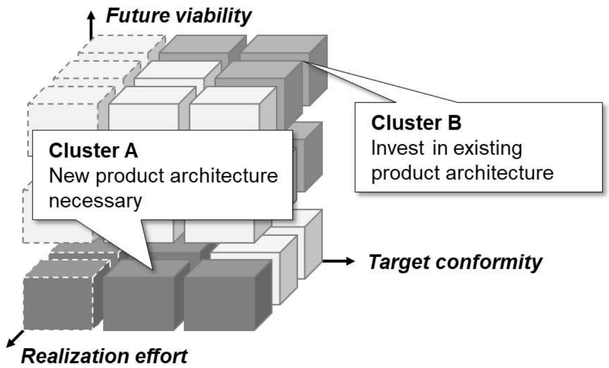

Fig. 4. Reference cases for technical product changes in the circular economy

This allows different clusters to be identified. For example, product changes with low effort, high future viability and high benefit represent the optimal state for the product architecture. If the effort increases, but future viability and benefit remain high, this can be seen as an investment in the future of the product architecture. If future viability decreases and implementation effort increases, the turning point of the existing product architecture is reached, up to changes that require a new product architecture.

Release strategies can be assigned based on the identified clusters. These may be immediate and future changes to the existing product architecture or changes that require a new architecture generation. Assigning the reference cases to release strategies enables systematic planning of product architecture generations. This makes it possible to assess the extent to which functional enhancements, improvements or guarantees can be realized on the existing product architecture.

In this context, the reference cases for functional integrations and improvements are particularly important. By analyzing the realizable reference cases in relation to the unrealizable reference cases over time, it is possible to identify at an early stage whether a new product architecture is necessary. Thereby Cumulative effects must be considered if multiple changes can no longer be realized on the existing product architecture generation, thus facilitating the planning of product architecture evolutions in the context of the circular economy.

5. Conclusion

In summary, this paper highlights the critical role of product architecture evolution planning in extending the lifespan of technical products within the context of the circular economy. The proposed conceptual framework offers a systematic approach for evaluating technical changes and their implications on the product architecture. By focusing on three evaluation dimensions - realization effort, target conformity, and future viability - manufacturers can make profound decisions regarding product upgrades for existing products and foreshadow the need for new product architecture generations.

The findings underscore the necessity of integrating modular design principles to facilitate upgrades while minimizing resource consumption. However, current methodologies reveal significant gaps, particularly concerning backward compatibility and future adaptability assessments of product architectures. As industries increasingly adopt circular economy principles, addressing these shortcomings will be essential for ensuring that products remain relevant and competitive over time.

Further refinement of the concept to increase its practicality and a deeper analysis of the implementation of technical changes to the existing product architecture are the next steps that are currently part of the authors' research activities. Limitations of this paper lie in the lack of specific criteria for the evaluation of the realization effort and future viability of the product architecture. Ultimately, this research contributes to the strategic planning of product architecture generations to enable manufacturing companies to extend the lifespan of their products through value added upgrades.

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