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Enabling cost-optimal product adaptation planning in Product Service-Systems

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Abstract

In recent decades, the accelerating consumption of natural resources has highlighted the need for economically and ecologically sustainable solutions. To address this challenge, adaptive upgrades during the lifecycle, particularly those embedded in product service systems (PSS), offer a promising way to extend product lifespans and reduce the need for new production. However, planning the timing and extent of the adaptation is crucial to ensure efficient implementation. This paper presents an optimization model for planning lifecycle-integrated adaptations in PSS with respect to economic and environmental goals, where environmental aspects are economically internalized. The model determines the optimal adaptation plan by determining the timing of adaptations, appropriate component versions, and the end-of-life strategy for dismantled components, considering user requirements, technological progress, and component wear. The application of the model is demonstrated using a material handling equipment use case. Significant operating cost savings can be achieved in different application scenarios through use-case-specific adaptation planning, showing the potential of adapting products in PSS.

Keywords: Product upgrade planning; Adaption; product service system

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1. Introduction

Between 1970 and 2019, the global extraction of raw materials tripled and is expected to increase by a further 70% by 2050, even though current resource consumption already exceeds the Earth's biocapacity by a factor of 1.7 [1,2]. A major problem lies in the use of extracted resources: extracted raw materials are often only used once before being discarded. A short useful life combined with low levels of reuse leads to a constantly high demand for new raw materials. In order to prevent a shortage of certain resources, strategies are needed to reduce resource consumption, whereby the extended use of already extracted raw materials to reduce the need for new resources constitutes a possible strategy to address the issue. End-of-life approaches in the circular economy are already a common way to achieve environmental savings [3]. Mid-of-life upgrades and product adaptation could offer a complementary strategy and the potential to extend the efficient service life of products by adapting them to changing requirements, thereby avoiding the need for early replacements with new products. Over time, organisms have developed a wide range of adaptive mechanisms, collectively described as phenotypic plasticity, that allow them to respond effectively to changing environmental conditions. Adopting proven biological strategies as a conceptual analogy for engineering contexts may open up significant potential for more flexible and sustainable products [4]. Product service systems (PSS) in particular offer associated services in addition to the product and enable holistic support throughout the product's life cycle. As a result, adaptation requirements can be identified and implemented at an early stage, which in turn extends product life, reduces the need for new raw materials, increases flexibility and improves

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customer satisfaction. This work examines a usage-orientated PSS, in which the provider retains ownership of the equipment and guarantees availability and performance over a defined leasing period. As part of this service offering, the proposed optimization model supports the provider by planning component adaptions during the use phase. In the following, the cost-optimal planning of product adaptations is examined in detail within the framework of an optimization model. The remainder of the paper is structured as follows: Section 2 distinguishes between product adaptations and upgrades and reviews the relevant literature. In section 3 the proposed approach is presented and in section 4 the results are discussed. The paper is concluded with a summary in section 5.

2. Related work

Adaptability is the ability to adapt a physical product to changing requirements [5, 6]. Typically, new requirements can be met or performance improved by appropriately adapting the existing product architecture by adding, replacing or removing components or modules [7]. An adaptable product is designed to be modified with minimal effort to meet changing requirements. A modular structure with easily exchangeable modules and the design of the interfaces to accommodate adaptations that may not be foreseeable at the time of development are cited as key influencing factors [5, 7, 8].

The upgradeability of a product refers to the potential and suitability for functional and performance improvements of a product by effectively and efficiently changing functional, physical and architectural features [9,10,11]. Depending on whether new functions are added to the product or whether existing functions are improved, this is referred to as a functional or performance upgrade [12]. Upgradeable products are characterized, among other things, by their robustness in meeting future requirements, as their often modular structure allows them to be replaced or expanded with new components [10,13]. The introduction of upgradeable product service systems (UPSS) extended the concept of upgradeable products to include the associated service [14]. The combination of product and service in PSS enables the fulfilment of long-term user requirements [15]. The process of creating an adaptable product is known as Design for Adaptability (DfA) or Adaptable Design (AD) [5,7,16]. Here, a possible adaptation of the product is already planned during its development in order to develop easily modifiable products with diverse requirement profiles, extended service life, and reduced demand for new or repeat purchases [5, 16]. With regard to adaptation, the authors distinguish between general adaptability and specific adaptability [5]. The general adaptability of a product refers to its ability to adapt to unforeseen requirements that were not known at the time of design. In contrast, with specific adaptability, possible requirements are already anticipated at the time of development. Design for Upgradeability (DfU) is used to improve the functional and physical suitability of a product for upgrades and its subsequent simple integration [17]. In their work, Khan & Wuest [18] identify four key characteristics for the design of upgradeable PSS: Customization, flexibility in design, ongoing validation of PSS requirements, and integrated development of product and service. If the upgrade step is carried out during product remanufacturing, this is referred to as design for upgrade remanufacturing (DfURem) [19,20]. Upgrade planning involves forecasting future technological trends and user needs to determine the timing and nature of upgrades to be offered to customers in order to maintain the long-term competitiveness of the product [21]. Beyond design considerations, several studies have investigated optimization approaches for upgrade planning. Contributions range from roadmap-based planning methods [21] to dynamic programming for cost-minimal component upgrades [22]. More recent work addresses data-driven methods in the context of remanufacturing [19] as well as simulation-based tools for evaluating upgrade cycles [23]. In addition, optimization and machine learning techniques have been applied to candidate selection for reconfigurable products [24,25]. However, these contributions are either narrowly focused on single aspects, limited to specific application contexts, or primarily conceptual. A comprehensive optimization framework that systematically integrates usage data and economic as well as environmental factors into upgrade planning across the product lifecycle is still missing. This gap is addressed by the present work.

3. Adaptive Upgrade Optimization Approach

The proposed adaptive upgrade approach based on [29] is applicable to a broad range of products and is not confined to a specific product category. In order to achieve the best possible adaptability of the products, this must be considered early in the development process. In this way, the prerequisites for later replacement of individual components are integrated into the products at an early stage of product development. A modular architecture with standardized interfaces constitutes a fundamental prerequisite for ensuring that individual modules and components can be easily replaced. This facilitates the flexible adaptation of products to new requirements or functionalities. Functional independence of components further supports this adaptability, where changes to a single component of a product do not affect the functionality of the others. In the literature, such a system architecture, in which modifications to one part of a product do not affect other parts, is referred to as a segregated architecture [5]. The proposed optimization approach consists of two sequential stages. In the first stage, a cost-minimizing plan is formulated for the adaptation of the product based on forecasts of expected usage. In the second stage, the plan is updated with the actual usage data of the product. Prior to the product's operational phase, detailed data on future usage is typically unavailable. For this reason, forecasts on the use of the product are used for planning purposes. To derive the cost-optimal adaptation strategy, a mixed-integer optimization problem is formulated, which simultaneously determines the times for an adaptation and the component versions to be employed in the replacement. The aim is to replace several components at the same time to minimize transportation costs, the cost of providing replacement products during the adaptation phase, and the expenses associated with final product inspection. Once the product enters operation, more detailed usage data becomes available. From this point, actual usage data replaces forecast-

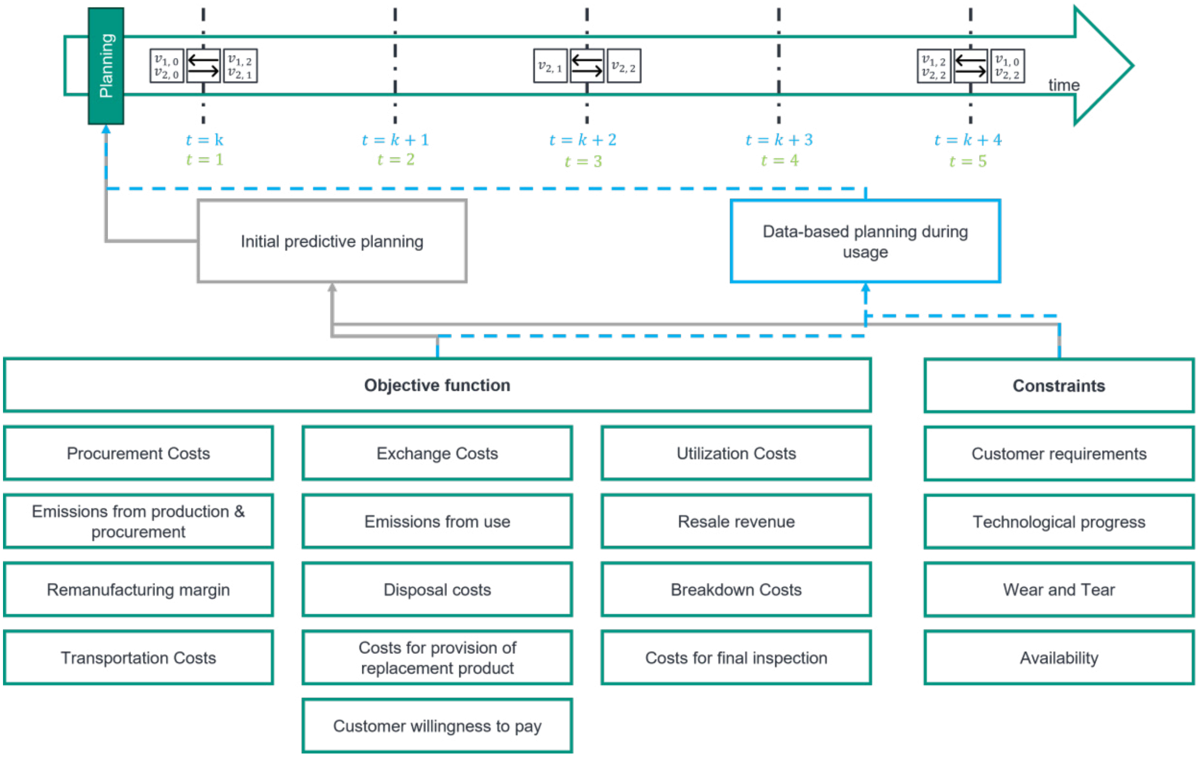

Fig. 1: Overview of the proposed optimization model

based planning, which enables more precise planning of adaptation requirements. To this end, an adapted optimization problem is formulated based on the optimization problem created in the first stage. The underlying model structure and decision variables remain consistent across both stages. The objective function takes a total of 13 factors into account. These can be subdivided according to whether they depend on the component version used or whether they are incurred once for the entire product if at least one component is replaced. The objective function reflects the monetized economic and CO2 pricing-based environmental targets, as well as customer requirements and includes a term for the monetary evaluation of the willingness to pay for their fulfilment. Figure 1 summarizes the structure of the proposed optimization model and its two stages. It shows how usage data, costumer requirements, technological progress, wear modelling and component availability are combined with the objective function and constraints to create the adaption plan.

The component-specific factors of the objective function characterize the direct dependency between the respective component versions to be installed and the associated costs. These include:

1. Procurement Costs: Purchase price of the component and transportation costs from the place of manufacture to the warehouse or installation site
2. Exchange Costs: Include expenses related to disassembling the old and installing the new component version. These include the time required for these two work steps and are measured on the basis of the labor costs incurred for disassembly and assembly, the depreciation value of the equipment required and the production overheads.
3. Utilization Costs: Include the costs for energy, operating resources and personnel, any fixed and downtime costs.
4. Costs for emissions from production and procurement: Emissions are monetized at a price per unit of CO_2 equivalent and include product-related emissions from the manufacturing process and transport-related emissions incurred during transportation from the manufacturing site to the warehouse or assembly site
5. Costs for emissions from use: Emissions are monetized with the price per unit of CO_2 equivalent and include all emissions allocated to the components, analyzed with regard to their specific emissions and the quantity of emissions caused by the use of a specific component version
6. Resale revenue: Used price at which components can be resold depending on age and use
7. Remanufacturing margin: Dismantled parts are reconditioned as part of the internal remanufacturing process and then sold in an as-new condition
8. Disposal Costs: Costs associated with a charged disposal of dismantled parts in case of no market for resale or if remanufacturing and subsequent resale cannot be implemented economically
9. Breakdown Costs: Expected costs related to unscheduled repairs in the event of component failure resulting in repair, downtime and bridging costs happening with component use time related probability

In addition to the component-specific factors in the objective function, there are three other costs that are incurred once and independent of the number of components to be replaced for the entire product:

1. Transportation Costs: Costs of transporting the product to the workshop or the service technician to the product
2. Costs for provision of replacement product: Costs for a required substitute product to take over the function of the product during the component replacement as the original

product cannot be used while one or more components are being replaced

3. Costs for final inspection: Costs related to the required final inspection of the product carried out to check the functionality of the product after the replacement of product components

The final component of the objective function takes into account the customer's willingness to pay for the fulfillment of their requirements. Based on the Kano model [26, 27] customer requirements are divided into must-be requirements, performance requirements and delighters. Must-be requirements are assumed by the customer to be fulfilled, which is why they do not influence their satisfaction and therefore also their willingness to pay if they are fulfilled. Performance factors, on the other hand, have a linear positive influence on customer satisfaction, which is why the customer's willingness to pay correlates linearly with the degree of fulfillment. Delighting factors have a non-linear but exponentially positive influence on the customer's satisfaction, which is why the customer's willingness to pay for the fulfillment of these requirements also increases exponentially.

After explaining the structure of the objective function for both optimization problems, the permissible solution space is limited by constraints. The constraints primarily serve to ensure that customer requirements are met. Analogous to the determination of the willingness to pay according to the Kano model, these are differentiated into must-be requirements, performance requirements and delighters. The quantitative requirements for the characteristics of the product are compared with its performance level. With regard to the must-be requirements, the performance level of the product must at least meet the customer requirements, as customers regard the fulfillment of the must-be requirements as a minimum criterion to be fulfilled as a matter of course. The fulfillment of the performance factors is expected by the customer, but is not mandatory, so that satisfaction correlates linearly with the degree of fulfillment. The model allows for the specification of a minimum degree of fulfillment. In the case of delighting factors, customers do not take fulfillment for granted, so that fulfillment offers the potential to differentiate the product from the competition. In the model, customer satisfaction and therefore their willingness to pay correlate exponentially with the degree to which these requirements are met, which is why they are taken into account and optimized in the objective function in the same way as the performance factors. Customer requirements correlate with technological progress over time. This shapes the product performance expected by the customer and is in turn reflected in the demand for component versions with different levels of performance. On this basis, the level of performance expected by the customer over time as a result of technological progress is modeled. The performance level of the product is determined by that of the components and decreases due to wear and tear during the product's service life. The Archard model [28] is used to model wear, which depicts it as a function of load. Since the relationship between wear and performance level is often application-specific, alternative modelling approaches may be considered.

Furthermore, the proposed optimization model offers the possibility of taking into account the availability of the component versions. This can be limited in time so that new component versions are only available at a later date, or obsolete ones are no longer available. This allows, for example, technological progress and the associated improvements to the components to be considered. Finally, the model defines ranges of the decision variables. These ensure the admissibility of the solutions. A detailed description of the full optimization model, including all variables and constraints, is made available in an additional reference [30].

4. Use Case

The following section illustrates the application of the presented optimization model using a material handling equipment use case. It demonstrates how a specifically tailored adaptation strategy can effectively reduce product life cycle costs.

4.1. Use Case Description

The following use case analyses three material handling equipment vehicles over a time horizon of 13 months. The adaptation planning of the wheels of these vehicles is optimized depending on the load. In total, each vehicle has 1 drive wheel, 1 support wheel and two pairs of load wheels, each subjected to different operational demands. As standard, all wheels are fitted with the material M2-tread, which is suitable for medium requirements. At the same time, a less expensive M1 tread, which exhibits higher wear and a more expensive alternative with lower wear (M3) are available as a replacement for each wheel. This makes it possible to adapt the wheels of the vehicles to different requirements with regard to the transport load and the distance traveled. In line with the previously discussed principles of Design for Adaptability and Design for Upgradability, the wheel system already has a modular and upgradeable design. The optimization model therefore focuses on making economically justified replacement and upgrade decisions for this design over the given period. The three scenarios for the three vehicles are presented in Table 1 as relative deviation of average total load of the wheels and travelled distance in relation to the forecast.

Table 1. Transported loads and distances traveled by the three vehicles.

	Forecast	Scenario 1	Scenario 2	Scenario 3
Avg. total load	100 %	−13 %	+2 %	+13 %
Distance	100 %	+ 24 %	−2 %	−21 %

At the end of their service life, three end-of-life recycling strategies are available for each wheel. These include selling the wheels at the material value, in-house remanufacturing with subsequent sale of the remanufactured wheels and disposal for a fee. Due to the possibility of selling at the material price, disposal is strictly dominated by the other two options in this use case.

4.2 Results of Predictive Upgrade Planning

For initial adaptation planning, it is assumed that the precise usage patterns in the later deployment scenario are not known at the time of the optimization. Therefore, forecasts on the basis of expectations about usage are used as inputs for the planning process. In the specific use case, the average use case of the three vehicles is used as the predicted operational scenario. Based on this data, the cost-optimal adaptation plan for the scenario under consideration over a leasing period of 13 months is determined using the formulated optimization model. All three components are replaced at the times t = 5 and t = 10, where t is given in months. Initially, the standard material M2 is used for all three wheel types. The first replacement takes place at time t = 5, as the wheels are so worn after five months due to the load and the distance covered that they no longer meet customer requirements at the next possible replacement time. Replacement is necessary at this point in order to meet customer requirements. In this case, M2 wheels are used again for all three components, as they offer the most favourable cost-performance ratio compared to the two alternatives at a medium requirement level. The wheels are also used for five months before they have to be replaced. The second replacement takes place at time t = 10. This time, material type M1 is used. This can be explained by the fact that the operating period at the costumer is limited to 13 months as well as the changed transported loads and driven distance. With a replacement at time t = 10, the wear from the last replacement is so low that the more cost-effective alternative is sufficient and the additional costs for a renewed use of M2 can therefore be avoided. In addition to the timing of the adaptation and the component versions to be installed, the optimization model also determines the end of life (EoL) strategy for the component versions dismantled during a replacement. It becomes clear that after deducting the costs for remanufacturing, it is the most economical option for all dismantled component versions even after accounting for associated costs. For this reason, this option is chosen as part of the optimization.

The predicted costs of the solution found per vehicle based on the average values show a reduction of approximately 8.45% compared to the repeated use of the standard type M2 over a leasing period of 13 months as procurement costs are the largest cost item in the use case.

4.3 Results of Evidence-Based Planning

In scenario 1, a vehicle is considered, which only transports a load of 13 % less than expected, but travels a high distance of 24 % more than forecasted. As a result, the load on the wheels deviates significantly from the original forecast. Re-optimizing the adaptation plan reveals considerable potential cost savings compared to using the standard material. The optimization results show that the creation of an application-specific adaptation strategy for the wheels of this vehicle leads to a cost saving of 38.41% compared to reinstalling the standard material M2. The cost advantage is mainly due to the choice of suitable materials and an optimized replacement strategy. At time t = 4, the initially fitted M2 wheels for all three-wheel types are replaced with M3 wheels, which are ideally suited for the high mileage due to their high-performance level and low wear. The dismantled rims are remanufactured. If the standard material M2 had been used, a total of three replacements per wheel type would have been necessary to meet customer requirements. Due to the optimized adaptation planning, however, the customer requirements can be met with just two replacement processes per wheel type. The switch to material type M3 results in higher procurement costs, but these are more than compensated for by the longer service life of the wheels and the resulting lower number of replaced wheels.

In application scenario 2, the adaptation planning of a vehicle is considered, which is largely used as forecasted. This similarity is reflected in the results of optimization problem: The adjustment plan is consistent with the forecast-based planning showing that in this case a replanning does not necessarily lead to further cost reductions.

In the third application scenario, the load is 13.04 % higher than forecast, while the mileage is 21.39 % lower. In this scenario two replacements are carried out at the times t = 5 and t = 9. Due to the lower load, wheels made from M1 are installed for the first replacement. This combination meets customer requirements at a more favorable price-performance ratio than M2 or M3. Due to the higher wear, however, they can only be used for four months, which is why they need to be replaced again in t = 9. At this point, identical wheels are installed, as they still represent the most economical solution. In the comparative solution, the second replacement occurs at t = 10. After the replacement, the wheels can be used until the end of the leasing period without falling below the required performance threshold, which means that there is an advantage to a later replacement in t = 10 with a new wheel. The adapted use of components achieves a cost saving of 16.30 % compared to the use of the standard variant.

5. Discussion and Conclusion

This paper presented an optimization approach for cost-efficient adaptation planning within PSS, which was validated through a practical use case in the field of material handling equipment. The methodology presented makes it possible to systematically plan adaptations along the product life cycle, taking into account economic and environmental targets. Through the incorporation of predicted as well as actual usage data, the model supports both anticipatory and reactive adaptation strategies, allowing for dynamic responses to real-world operating conditions. Due to the prototypical sensor setup and high-frequency data acquisition resulting in a large volume of usage data, only a limited number of products could be analysed. Nevertheless, the results suggest that there is potential for adaptation and that the proposed optimization is functional. The use case demonstrated that tailoring component selection and end-of-life strategies to actual requirements can lead to substantial cost reductions compared to the continued use of a single standard component version. This not only improves economic goals, but also contributes to sustainability by reducing the demand for raw materials and supporting circular economy practices. In summary, the developed optimization model offers a valuable tool for the sustainable configuration of PSS. It allows companies to respond more effectively to increasing demands for flexibility, resource efficiency, and customer-centric solutions. In addition to the presented optimization of adaptation planning, future work should address the integration of adaptive upgrades into viable business models. For manufacturers, this requires creating offerings that combine technical adaptation strategies with service-based revenue mechanisms. A holistic approach is required to demonstrate that adaptive product upgrades can reduce costs and environmental impacts while creating long-term value for all stakeholders.

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