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Phenotypic Plasticity as a Blueprint for Adaptive Product-Service Systems

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Abstract

Identical products often operate in vastly different environments and use cases, exposing them to uneven and sometimes unpredictable mechanical or functional loads. This results in inefficiencies and only partial fulfillment of customer needs. To improve sustainability and maximize customer satisfaction, future products must be capable of adapting to changing operating conditions. Biology offers a wide array of midlife adaptation strategies, known as phenotypic plasticity, that enable organisms to maintain or enhance their performance over time. Building on this concept, phenotypic plasticity mechanisms were systematically analyzed and the findings were translated into an engineering context. The accompanying comparison model facilitates the selection of adaptations by providing a transparent, multi-criteria evaluation framework. The result is a four-step methodology that guides companies in implementing adaptive capabilities into product-service systems.

Keywords: product-service systems; flexibility; phenotypic plasticity; sustainability; upgrade; product adaption; bionics

1. Introduction

The ongoing depletion of resources caused by human activity highlights the need for long-term sustainable strategies. In the context of capital goods, this raises the question of how products can be designed and operated to extend their life cycles efficiently. [1,2]. Biological principles offer inspiration for environmentally friendly and efficient industrial products by imitating natural elements, phenomena, or organisms [3]. In general, bionics introduces a new way of thinking for problem-solving [4] and provides diverse inspiration for implementing more sustainability into technological products and processes. One of the easiest examples is hibernation, which can be transferred into technology as a standby-modus to save energy [5]. Biological optimizations from one generation to the next, known as evolutionary processes, have already been applied in various technological contexts, for example, as an optimization method during the system design phase [6]. However, the biological optimization within one lifecycle (LC) of an organism has still rarely been transferred, despite there being just as much potential inspiration. Customer needs for a purchased product are dynamic over time, and currently, enterprises are unable to react to these changing requirements during the use phase [7]. Sold products are usually used in a wider range of applications than originally intended when they were developed. However, the products are mostly unable to adapt to the various applications, nor to respond to changing environmental conditions and requirements during their use. With the concept of selling purely physical products the producer in general has no interest in optimizing the products that are already in use by the customer. When the scope extends to the entire product life cycle, cooperation that goes beyond production itself is necessary [8], and a link between industrial value creation and product adaptation becomes essential. The first step towards the goals of flexibility and sustainability is the change from purely physical products to product-service systems (PSS).

1.1. Product-service systems as a basis for flexibility

A PSS is the combination of a tangible product and intangible services, which together serve the purpose of

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satisfying stated customer needs [9,10]. Not the product is sold to the customer anymore, but a solution for a given need. On the one hand, PSSs offer many more design options than purely material product sales [11]; on the other hand, their new solution-oriented approach and detachment from the actual product give the company itself the incentive to focus on sustainability-oriented process optimization [10,12]. The incorporation of additional services presents opportunities to reduce material consumption and increase energy efficiency [13]. Transitioning to a PSS model encourages providers to optimize their offerings throughout their entire LC. [14]. Additionally, the relationship between the provider and customers changes [15]. With the PSS, the customer and provider interact with each other throughout the entire usage phase to achieve the best possible solution. This integration leads to long-term business relationships and, simultaneously, increased customer loyalty towards the provider brand [14]. Ideally, there is also a continuous exchange of data, allowing services to be adapted to requirements as quickly as possible, while extending the product's service life at the same time [14].
A key advantage of a PSS is the possibility of being parameterized, readjusted, or supplemented with additional services throughout the life cycle, in line with individual and dynamic customer needs [16]. PSSs combine sustainability with customer satisfaction, but the timing and cost–benefit of use-phase adjustments remain unresolved.

1.2. Phenotypic plasticity and the use of bionics

Inspiration to answer those questions is found when looking into nature. Organisms can implement changes during their life and thus optimize their fitness level. These mechanisms are part of the collective concept of phenotypic plasticity (PP). PP describes the ability of organisms to develop different phenotypes in response to changing environmental conditions. The genotype, i.e., the genetic material, remains the same, but the phenotype is adaptive. [17,18]
Phenotypes encompass (i) the morphology, i.e., the form and structure of the organism, (ii) the physiology, i.e., the internal processes in the organism, (iii) the behavior, (iv) the life history, and (v) the ecological relationships with other individuals [17,19]. Accordingly, the phenotype comprises not only material aspects that are visible in the organism's appearance, but also immaterial aspects. All these facets of the organism can change during PP. To initiate an adaptation of the phenotype, a specific trigger is necessary. This can be an external or internal, harmful or non-harmful stimulus [17]. Once the current environmental situation and the individual's own condition have been perceived and evaluated, an appropriate response is initiated. The phenotype with the highest probability of representing the fitness optimum in the given environment is selected [20]. In its original understanding, fitness itself comprises the chances of survival of the organism and its offspring, the degree to which the organism fits into its environment, and its performance within it [21]. In the context of considering the totality of all possible environments, organisms with the ability of PP have the advantage of achieving a better average fitness than organisms with a fixed phenotype [22]. The ability to adapt is limited by costs and by the ability to reliably perceive environmental stimuli [20]. Ultimately, whether and when adaptation occurs is determined by the cost-benefit ratio [20]. With this inspiration, PP offers answers on how to implement more flexibility in the use phase of PSSs. This knowledge should be used for the following to develop a methodology that guides companies in implementing adaptive capabilities into PSSs.

2. Related work

In the current literature, various possibilities have already been discussed, that implement optimization of PSSs during their utilization phase, thereby making them more flexible in their functionalities and prolonging product usage for the customer. The first possibility discussed is self-correcting systems. Bell et al. distinguish between self-healing mechanisms, self-repairing mechanisms, and physical redundancy. Products with such corrective mechanisms achieve higher reliability and a longer service life. [23,24]
With the help of upgrades, it is possible "to consider not only current but also future customer, user, and provider needs" [23] and extend the value-creating lifespan of the product. Upgrades are also frequently discussed in the context of various circular economy (CE) strategies [24]. Upgrades can, for example, be implemented by adding, removing, or replacing modules, thereby integrating new functionalities. This enables the reduction of necessary resource quantities during production and the amount of accumulated waste. Overall, this contributes to sustainability. [25–27]
A third possibility for more flexibility is reconfiguration. During the reconfiguration process, the arrangement of the system's components is changed. It is essential to note that only components already present within the system are modified [28]. With the possibility of reconfiguration, the provider thus has the expertise to offer a PSS that can respond to changing circumstances while maintaining true to its performance [29].
Intelligent PSSs are another option identified in research for making PSSs more flexible. Intelligent PSSs are "an IT-driven value cocreation business strategy consisting of various stakeholders as the players, intelligent systems as the infrastructure, smart, connected products as the media and tools, and their generated e-services as the key values delivered that continuously strives to meet individual customer needs in a sustainable manner" [30]. In contrast to these approaches, the PP-based methodology offers a unique perspective. Rather than focusing solely on reactive correction (self-healing) or standardized modular substitution (upgrades and reconfiguration), it provides a principles-based approach to anticipating and balancing adaptation options throughout the entire usage phase. This approach emphasises LC-wide optimisation and sustainability trade-offs.

3. Method

For our own model, the intelligence and variety of nature should be the inspiration for more flexible PSSs. Therefore, a bionic process is used in order to develop the methodology for implementing adaptive capabilities into PSSs. The origins of the desire to utilize and imitate the principles, functions, and structures of nature date back far into the past [31]. Despite considerable advances, the field of bionics still harbors substantial unexplored potential. In this study, the degree of abstraction is very high, as the collected examples of PP are not intended to be modeled in a close-to-natural way, but merely their principles and characteristics should be made transferable to PSS. Wanieck [4] differentiates between three degrees of abstraction. This study matches his third degree of abstraction, because the lowest proximity to the natural model and at the same time the highest application potential is present. Beismann [32] differentiates between technology pull and biology push as the two main bionic approaches. Within the biology push approach an inspiring biological model is the starting point. In this study a clearly defined objective within the technical domain builds the motivation for the bionic process. Therefore, a technology pull and not a biology push is given. Thus, the technology pull framework of Wawers [5] is chosen for the further procedure. The biological project part, consisting of brainstorming ideas, analysis, and abstraction, is iteratively repeated until the framework and all necessary characteristics and principles for the final methodology are found. The resulting methodology will be described in the following. To ensure focus and applicability, the methodology is restricted to the use phase of PSS is subject to multiple boundary conditions, including the availability of reliable operational data, compatibility with existing business processes, and the maturity of digital infrastructures in the adopting industry.

4. Four-step optimization methodology towards more adaptive PSS

The structure of the methodology is derived from the principles of PP adaptation mechanisms. Each of the adaptation mechanisms of PP represents an optimization process. This process can be subdivided into the following four steps: 1) Trigger: Identification of optimization potential. 2) Unfolding of new potential target states. 3) Assessment of possible adjustments and selection of the new target state. 4) Integration and control of the selected adjustment. The same four steps can be followed when a PSS should be adjusted to its changed environment or customer needs. So, this subdivision as a common denominator between biology and technology will further be used as basic structure for the methodology. In the following examples adaptation mechanisms and principles of PP are considered in more detail: The chameleon is widely known for its ability to change the color of its skin. Possible triggers for this behavior include light and temperature conditions, as well as the presence of prey, predators or conspecifics. The color change can have a direct benefit in terms of the amount of light absorbed or reflected. The amount of absorbed heat radiation influences the chameleon's activity time. However, social communication also occurs through color changes. For example, camouflage is an advantage when perceiving predators and catching prey. Neuronal and hormonal mechanisms control the change. The skin itself consists of various specialized cell types, which can produce the different color characteristics through their interaction. [33]

Daphnia also show a reaction against predators. It initiates an adaptation of its body shape in response to perceiving kairomones. The formation of a helmet/neck tooth is a morphological adaptation that is reversible and repeatable and is therefore also called cyclomorphosis. The form can vary in cycles. Overall, the helmet makes it more difficult for daphnia to be eaten by existing predators, thus increasing its chances of survival in danger situations. [34]

Plants exhibit various PP mechanisms. A common example is root system plasticity, which enables the efficient uptake of nutrients and water. This should be as cost-efficient as possible. “To achieve this goal, maximize productivity, and adapt to variable challenging conditions, plants rely on root phenotypic plasticity. This includes changes in root morphology, growth angles, diameter, elongation, branching density, and turnover rate. In simple terms, a plant root system is a dynamic structure that can change its branching structure in response to changes in biotic and abiotic conditions” [35].

These and many other PP mechanisms were collected, analysed and conceptualised iteratively. The iterations continued until no further relevant adaptation patterns emerged within our scope. To develop the four-step methodology, we used a purposefully selected, representative set of 26 PP examples, drawn from the most frequently cited and common cases in the literature. Together, these examples capture the breadth required for this study. The four steps and their biological counterparts are outlined below.

1) Trigger: To answer the question of which criteria determine and influence the identification of a deficit, potential triggers of PP were collected and grouped together. A questionnaire was developed that enables a comprehensive evaluation of factors that influence the identification of a deficit. The potential triggers can be grouped into four categories. One frequently occurring trigger is temperature [36], a physical and external stimulus. However, external triggers can also originate from other organisms or serve as an input factor, such as the food of an organism [36]. The last group is built up by internal signals, such as the injury of a zebrafish, which serves as a trigger for needed regeneration [37]. The categories of external, internal, and input triggers help not only to focus on the PSS itself, but to extend the scope of consideration to the existing environmental situation, interactions, and all current input variables and to incorporate these into the assessment of the overall situation. The questionnaire developed consists of the following seven queries: (1) How many potential triggers should be included in the consideration? (2) What are the interactions between the influencing variables? (3) How predictable and reliable are the triggers? (4) Does the trigger enable a preventive adjustment, or does it signal the need for a reactive adjustment? (5) Is the trigger an indication of a critical situation? (6) Does the trigger indicate a deficiency, or does it enable the realization of optimization potential? (7) Is the trigger influenced by the interaction with other agents? These seven questions can be used by the PSS provider to form a comprehensive picture of the situation expressing the need or possibility for optimization through adaptation of the PSS. Additionally, a preliminary assessment of the characteristics, that the later chosen adaptation should fulfill, can be made.

2) Potential Adaptions: Once a deficit or optimization potential has been identified, the next step is to explore suitable mechanisms for integrating greater flexibility into the PSS. This second step provides an overview of possible adaptation options. The 26 examples collected are grouped into ten clusters, each of which is summed up with a clear profile. The profile takes the following characteristics into account:

Reversibility: If the inducing environment goes back to the non-inducing environment, does the phenotype reverse with it or does it stay fixed? [20]

Labile or fixed: Can the trait establish only once in the lifetime and is then fixed, or is it labile and can change repeatedly? [36]

Continuous or discrete: Can the response be described with a continuous reaction norm, or does the trait only exist in a limited number of discrete forms? [20,36]

Based on an analysis of 26 examples of phenotypic plasticity, ten adaptation profiles were derived and aligned with TRIZ principles [40]. These profiles differ in terms of their degree of reversibility, fixity and continuity, with each one exemplified by a biological mechanism. Consolidation (TRIZ 5), for instance, describes reversible, labile and gradual changes, such as the symbiosis of legumes. Universality (TRIZ 6) is characterized as reversible, labile and discrete, as demonstrated by the colour change of chameleons. Prior action (TRIZ 10) involves irreversible, fixed and discrete adaptations, such as temperature-dependent sex determination in turtles. Profiles such as dynamicity (TRIZ 15) and feedback (TRIZ 23) are both reversible, labile and continuous. These are represented by helmet formation in Daphnia and the movement of Mimosa pudica, respectively. The self-service profile (TRIZ 25) is irreversible, labile and discrete, as observed in the regeneration of zebrafish fins. The transformation of properties (TRIZ 35) refers to irreversible, fixed and discrete changes, such as the metamorphosis of axolotls under stress. Periodic transformation (TRIZ 19 and 35), such as the seasonal change in fur of hamsters, is reversible, labile and discrete. The inert environment (TRIZ 39), as demonstrated by tardigrade cryptobiosis, and composite materials (TRIZ 40), as seen in the division of labour in insect colonies, represent forms of reversible, labile and discrete adaptation.

3) Assessment and selection: The third step of the methodology involves answering the following question: Based on which evaluation criteria can a well-founded selection of one or more adaptation principles be made? Schneider [20] sums up the important factors with the following statement: „A critical challenge organisms face in heterogeneous environments is assessing the cost–benefit ratio, or whether or not the ‘cost’ of expressing a plastic response outweighs its potential benefits.“ In order to optimize the PSS in its usage phase, a more detailed look allows the assessment of potential adaption mechanisms. The costs can be further differentiated. DeWitt et al. [22] provide a logical structure by differentiating between a total of five types of plasticity costs: Maintenance costs, production costs, information acquisition costs, developmental instability, and genetic costs. The first three of them can be synonymously transferred into the technological context. The developmental instability encompasses all costs arising from errors in the adaptation. For example, recorded data can potentially provide an unreliable signal resulting in an adjustment being implemented too early. The genetic costs encompass all expenses associated with undesirable yet unavoidable side effects. These include compatibility issues, increased long-term maintenance and temporary system downtime after adaptation. Such effects arise when optimising a feature or function unintentionally affects other seemingly independent features or parts of the system that were not directly targeted by the adjustment. The benefit of integrating an adaption into the PSS can also be further differentiated. As already stated in the motivation, sustainability and the customer‘s needs are important goals to achieve. However, general economic aspects, such as reducing costs, are also important and in the interest of the PSS supplier. All put together, Pialot and Millet [26] call it the satisfaction of „the trio ‚attractiveness for consumer, environmental gains and economic benefits‘“. For the theoretical evaluation framework in 4.5. the benefit increase should be defined as the sum of those three aspects. The cost input is the sum of the five cost types as defined by DeWitt et al. [22].

4) Integration and regulation: After the assessment and selection of adaptation mechanisms, the final steps are implementation and, possibly, regulation. The following question should thereby be the focus: “What aspects influence the integration and regulation of the adaptation?” As in the first step of the methodology, an overview of PP regulatory mechanisms and a questionnaire were designed for this purpose. The analysis of the regulation mechanisms shows different time horizons. While the color change of the chameleon, which is controlled by its nervous system, happens within a few seconds [33], epigenetic processes, which can act like an on/off-switch for genes [38] lead to more long-term changes. An example here is the temperature-dependent sex determination of turtles [39]. The developed questionnaire consists of the following: (1) Should the adaptation be actively initiated or should the system passively follow the development of changed environmental conditions? (2) What time aspects should the adaptation fulfill (delay time, speed of adaptation, time in adapted state)? (3) What is the regional range of the adaptation? (4) Does the adaptation involve a connection to other agents? (5) In which of the six BioTRIZ fields of operation does the adaptation fall? (6) Is regulation needed for the adaptation? Once all six of the questions in the questionnaire have been answered, there is clarity about the criteria that must be taken into account when implementing and potentially regulating the adjustment mechanism. Conclusions can be drawn from the answers to each question regarding what needs to be considered when integrating the adjustment. Industrial adoption further requires attention to organizational constraints, regulatory compliance, and the balance between short-term implementation costs and long-term LC benefits.

4.1. Theoretical evaluation framework

Finally, the theoretical, multi-criteria evaluation framework will be described. It accompanies the PSS provider through the first three steps of the developed methodology and helps to compare and select between possible adaptation mechanisms. The current state of the system is depicted along the x-axis of the model. It provides information on whether there is a need for adaptation, thus representing the result of the first step in the developed methodology. If the current state is at the origin, it is neutral. However, the further away the current status is from the origin, the greater the identified deficit. The deficit is intended to express the difference between the functions fulfilled by the system compared to the functions desired by the system user. The y-axis shows the trade-off between the benefit increase, which can be accomplished through adaptation, and the cost input directly linked to the adaptation. On the y-axis, the difference between the benefit increase minus the cost input is plotted, so that a downward shift along the y-axis represents the cost input and an upward shift along the y-axis represents the benefit increase. The starting point before any adaptation implementation is at the level of origin. When using the framework, the following steps should be performed: (0) Define and enter two grey boundaries (1) Enter current state/deficit along the x-axis. (2) Enter the limits of the implementation area (green area). (3) Enter the target state after adaptation. (3a) Map cost input for adaptation. (3b) Map benefit increase from adaptation. (3c) Map deficit correction through adaptation. (4) Enter other possible target states reached by other adaptations. (5) Comparison between and selection from possible adaptations. The results of steps zero to three can be seen in Figure 1.

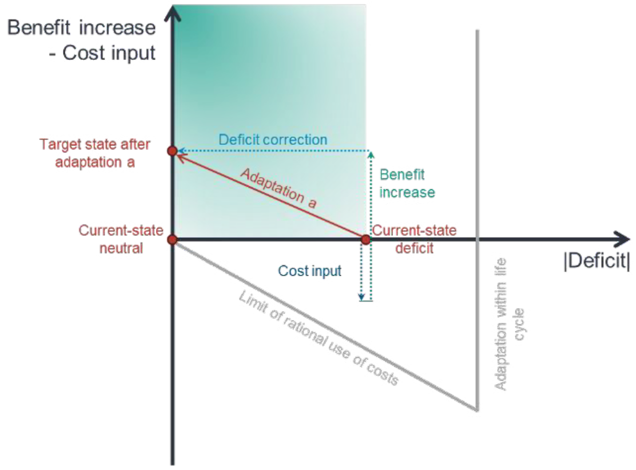

Fig. 1. Theoretical evaluation model x- and y-axis

The two grey limits are defined by the provider before an adjustment is even considered. The grey boundary at the bottom represents the maximum cost input that should be used, based on the size of the deficit. The grey limit to the right represents the deficit level beyond which it is more reasonable to switch to a new system generation. In step one, the current state of the system is observed and mapped onto the x-axis. Now, the implementation area (green area) can be entered. As the deficit is to be optimized, a vertical border runs upwards from the deficit. The border from the deficit to the origin illustrates the following: The increase in benefit achieved by the adaptation should be at least as great as the costs incurred for the adaptation. If these are equal in amount, the new state after the adaptation lies on the x-axis. The new state after the adjustment should be at least here, but preferably above the x-axis. The further above the x-axis the new state lies, the greater the increase in benefit. In step three, the criteria to evaluate one adaptation are entered into the coordination system. To determine the new state the adjustment brings the system to, according to the deficit (red arrow), proceed in three sub-steps. The first step is to enter the cost input into the model (indicated by the dark blue interrupted arrow). Starting from the deficit, this represents a vertical line downwards. The second step is to depict the increase in benefits. Now, starting from the end point of the dark blue arrow, the increase in benefit represents a vertical line pointing upwards (vertical green interrupted arrow). A third effect of the adjustment is its influence on the deficit. Thus, the third variable to be entered is the deficit correction (indicated by the horizontal blue interrupted arrow). Starting from the end point of the benefit increase, this should be entered horizontally and pointing to the left. The end of this arrow now represents the target state that can be achieved by implementing an adaptation. Starting from the deficit and following the course of the three interrupted arrows shown, the new state, which can be reached by implementing one adaptation, is achieved. With the same procedure, different possible adaptations can be mapped into the coordinate system. Adaptations with target states not within the implementation area should not be considered further. The adaptations that cross the grey border of rational cost usage should also be eliminated. When several possible new target states are mapped in the coordinate system, they can be compared to each other. The further upwards and the nearer the target state is to the y-axis, the better. Not only one, but also several adaptations can be selected for implementation. Not yet mentioned is the third dimension of the framework. The z-axis is used to subdivide the PSS into its different modules. This enables more detailed considerations, as illustrated in Figure 2.

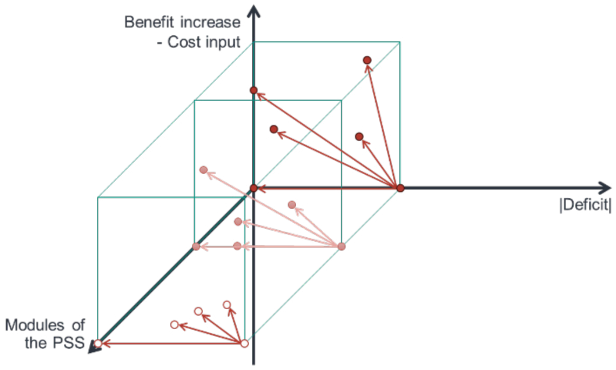

Fig. 2. Theoretical evaluation model

Based on the plotted scatter map of target states, it is also intended to select one or several adaptations for further implementation. The method was further refined through its application in two use cases, during which existing upgrades were examined and new potential enhancements for development were elaborated.

5. Conclusion and Discussion

In this study, a methodology for systematically transferring adaptation principles of PP to configuration-dynamic PSSs was developed. This methodology represents an initial approach, developed based on the principles of PP, for adapting PSSs to changing environmental conditions and requirements during their utilization phase. The result of a four-step methodology and the multi-criteria evaluation framework guide companies in implementing adaptive capabilities into their PSSs. Although ten adaptation mechanism profiles were identified, the classification does not claim to be exhaustive. In the biological context, the mechanisms underlying PP have not yet been conclusively categorized, which limits the completeness of the current model. A more comprehensive analysis and structured subdivision of PP mechanisms would be required to ensure full coverage of possible adaptation pathways. Furthermore, the theoretical model developed within this study includes variables that can currently only be represented on an ordinal scale. This limits the model's quantitative analytical capabilities. As a next step, operational metrics (e.g., cost savings, downtime reduction, customer benefit indices) can be embedded into a support tool to transform the semi-quantitative framework into a fully quantitative model for instance by applying established decision-support methods such as AHP or MCDA. The introduced concept increases flexibility during the use phase, but also raises questions regarding its implications for other life cycle phases, particularly the end-of-life and product design phase. Furthermore, evaluating the business model for adaptive PSS and upgrade services is essential to demonstrate their value to organizations.

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