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# A VARIABILITY MODEL FOR INDIVIDUAL LIFE CYCLE PATHS IN LIFE CYCLE ENGINEERING

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**ABSTRACT**

Life cycle properties are becoming increasingly important for the success of a product. They are determined during development, but their impact – and thus value – only becomes apparent in later life cycle phases. Life cycle engineering is concerned with designing such product properties in early stages of design. However, the life cycle paths of individual products from the same product type increasingly diverge, due to differing product usage, personalization and software or hardware updates. The expected and realized value of certain life cycle properties might vary greatly within the same type of product. Thus, this paper addresses how such individual life cycle paths can be made accessible to product system designers in the context of LCE, to evaluate and determine valuable life cycle properties. A meta model is developed to describe divergent life cycle paths of individual products and investigate, how to identify the possible, future life cycle paths in early stages of design and how to incorporate them in LCE. The approach is applied to the design of a door panel for passenger cars. Suitable life cycle properties and their associated designs were evaluated and determined, with respect to the expected, individual life cycle paths.

## 1 INTRODUCTION

The evolution of a product during its life cycle is central to life cycle engineering (LCE). LCE is an engineering approach, which seeks to incorporate life cycle properties into a product in early stages of design [1]. Life cycle properties are non-functional properties of a product system or its parts. They are determined during development. Yet, their impact – and thus value – only becomes apparent in later life cycle phases [1, 2]. Examples are customizability, serviceability, reusability as well as the product's recyclability (see e.g. [1–3]). Life cycle properties are becoming increasingly important for the success of a product [4, 5]. On the one hand, additional life cycle properties such as reusability, repairability, and remanufacturability currently come to the fore due to the increasing demand for sustainable and circular products [6, 7]. On the other hand, product costing focus shifts from a development and manufacturing perspective to an overall life cycle perspective due to Servitization and the development of product-service-systems (see e.g. [8]). Life cycle engineering focuses on determining such properties in the early (concept) stage of product development, when product attributes and costs can still be influenced to a large extend [1]. Thereby, rebound effects as well as further dependencies between the life cycle properties and other design goals must be considered [3, 9]. Current methods and tools for LCE support in identifying and resolving such trade-offs during product development. They analyze the life cycle of the product under development and identify valuable designs for the life cycle properties.

However, the life cycles of individual products from the same product type increasingly diverge. A natural source of this divergence are the circumstances of the individual product usage. They define, how long an individual product lasts, whether it is maintained, resold, put to a second-life use, or recycled. Additionally, mechatronic product systems like cars are increasingly personalized and updated. They evolve individually during the life cycle through reconfiguration, software updates and hardware upgrades. This further increases product variations in the field (see e.g. [10]). As a result, the expected and realized value of certain life cycle properties might vary greatly within the same type of product. A design problem in the conceptual phase of product development results, regarding LCE: A system concept must be determined, which effectively leverages the life cycle properties over all possible, individual life cycle paths. To achieve this, the individual paths must already be known and considered in concept development. Otherwise, the value of certain life cycle properties cannot be evaluated properly. Rebound effects, occurring between individual life cycle paths, are ignored and the life cycle properties are not realized effectively. Trade-offs between the properties and their suitability for different life cycle paths are not identified and resolved. Thus, we address how such individual life cycle paths can be made accessible to product system designers in the context of LCE. Firstly, a meta model is developed to describe divergent life cycle paths of individual products. Subsequently, we investigate, how to identify the possible, future life cycle paths in early stages of design and how to incorporate them in LCE.

## 2 LITERATURE REVIEW

Jeswiet [11] provides a fundamental definition of the term Life Cycle Engineering (LCE), summarizing forgoing research: Life Cycle Engineering sums the “engineering activities which include the application of technological and scientific principles to manufacturing products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste.”. Thus, product development plays a central role in LCE as this phase defines e.g. a product’s environmental footprint in large part [12]. Consequently, LCE can be understood to comprise product development activities and decisions, keeping certain product properties such as sustainability aspects in sight while considering single or multiple product life cycles [13–16]. Pivotal elements of LCE are life cycle properties. “These properties are not the primary functional requirements of a system’s performance, but typically concern wider system impacts with respect to time and stakeholders that are embodied in those primary functional requirements” [2]. Typical life cycle properties, which de Weck et al. [2] describe as “-ilities”, are amongst others “Reliability”, “Flexibility”, “Durability” and “Usability”. Regarding product systems that are supposed to fulfill requirements of a Circular Economy, these life cycle properties could be enhanced or derived, by considering circular strategies like “Repurpose”, “Refurbish”, “Re-use” and “Rethink” (see e.g., [6]).

LCE has to face new challenges in terms of considering additional life cycle phases and states in product design, for instance resulting from sustainability-oriented concepts such as Circular Economy [7, 17, 18]. This is caused by the need to extend product life cycles to keep products, components, and materials in use as long as possible. This is expedient with the requirement to consider additional phases of e.g. product usage already in product development [19, 20]. Thus, the Circular Economy paradigm amongst others represents a challenge for engineers to integrate a holistic life cycle thinking approach [9]. This is exemplified by the research of Halstenberg et al. [8], who developed a methodology for the development of Smart Services, which addresses Circular Economy strategies. They propose Model-based Systems Engineering (MBSE) procedures, notations and tools as an adequate foundation [8]. Model-based Systems Engineering (MBSE) describes the model-based and IT-supported application of systems engineering methods [21] to optimize modeling and foster a common understanding and a traceability for the system under development [22, 23]. As such, holistic approaches for MBSE generally consist of a method, a (software) tool and a (graphical) modeling language [24], which are in this paper’s focus. Other methods, pointing in the same direction as Halstenberg et al. [8] with MBSE for LCE, are for example Bougain et al. [25] and Yvars et al. [26]. Thereby, Cerdas et al. [27], Dér et al. [28], and Tao et al. [29] for example take divergent, individual life cycle circumstances in LCE into account. Yet, their perspective is data focused and simulation driven. They are not suitable for early stages of design, when this data is not present and detailed simulations are not expedient. Thus, our analysis led us to the insight that there is a need for product development, and LCE in particular, to take the alteration of individual life cycles over time into account. To the authors' understanding, this has not been covered by the findings of Halstenberg et al. [8], Cerdas et al. [27], Dér et al. [28], and Tao et al. [29].

To summarize, different approaches for the evaluation of life cycle properties as well as methodologies for life cycle-oriented design exist. They analyze and model the general product's life cycle during development or evaluate the individual life cycles in detail via simulations and collected data. Yet, to the best of our knowledge, none of them proactively incorporates divergent life cycle paths of individual products in early stages of concept development to determine life cycle properties. As such, we aim to answer the following research question: How can divergent and individual life cycle paths be described and incorporated in LCE, to evaluate and determine valuable life cycle properties?

## 3 APPROACH

The goal of our approach is to incorporate individual life cycle paths into LCE. The life cycle paths are employed to determine and evaluate valuable life cycle properties with respect to all possible, individual life cycle paths. The literature review indicates that there is a sufficiently large and profound body of knowledge, dealing with LCE approaches based on generic (i.e., non-individual) life cycles. They build up on a systemic and model-based understanding of the product and its life cycle. Thus, we follow an orthogonal approach. The already existing methodologies and models are supplemented by developing a meta model for individual life cycle paths. This meta model can be used as a complement to already existing product and life cycle models. Subsequently, the meta model is associated with a methodology, which describes, how to setup and utilize such a model in present LCE approaches.

Overall, our approach is based on the idea of MBSE. The individual life cycle paths are described as models. This creates transparency by abstracting the most important aspects of the individual life cycle paths. Furthermore, it allows analysis of the modelled paths and interference towards the influence on the life cycle properties. Systems engineering provides the conceptual framework to link our approach with the already present LCE approaches [9, 30].

### 3.1 Meta Model for Individual Life Cycle Paths

In MBSE, a model stores all the available information and knowledge about the product to be developed [22, 23]. The systems engineering methodology then generates, interacts, and alters the model throughout the design process, to integrate information and knowledge and evaluate the current design. A meta model defines the representation scheme for the information and knowledge within the product model. For LCE such a representation scheme should include, among other things, information and knowledge about the life cycle performance of the product (see e.g., [27–29]). Thereby, one challenge is, that the associated, individual life cycle paths must be depicted in early stages of design, before the product is developed. The individual life cycle paths are only partially known and uncertain.

We define an individual life cycle path as a sequence of multiple life cycle states. A life cycle state is a temporal demarcated, feasible situation, in which specific properties of the product are requested by external stakeholders. These external stakeholders are for example the customer, the legislative body, or the manufacturing department. The union of all required properties from all life cycle states equals the overall product requirements. A life cycle phase aggregates the life cycle states, whose required properties are driven by the same set of external stakeholders. Thus, multiple life cycle states for one life cycle phase can coexist.

In contrast, a life cycle property is a non-functional, system wide property, whose impact only becomes apparent in later life cycle phases [1, 2] (see section 1 and 2). Life cycle properties are realized through specialized approaches (see e.g. [8, 25, 26]), which translate the abstract objective of the life cycle property into a product's design. Thereby it is important to design the product in such a way, that it generates a real positive impact on later life cycle phases. Yet, the life cycle phases consist of different life cycle states, which might be passed individually by each product. Thus, incorporating a life cycle property in the product's design is only of value, if it supports the realization of the required properties of a sufficiently large portion of the life cycle states. Put vice versa, the required properties of the life cycle states define the value of a life cycle property and how it is best implemented. Thus, the life cycle properties must be evaluated and implemented according to the given life cycle states and their probabilities. This is supported, by modeling the life cycle states' probabilities as well as the relationship between life cycle states and life cycle properties explicitly.

Fig. 1 depicts the elements of our meta model. Conceptually, a model for LCE with individual life cycle paths is divided into three parts: The product architecture, the variability model and the life cycle model. Each part describes a certain aspect of possible product states throughout the life cycle phases. The product architecture models the requirements, functions, components and generic physical structure of the product to be developed (see [10, 31]). It represents the static part of the design. We assume the meta model for the product architecture is externally given and thus not part of our meta model. Yet, the variability and life cycle model of our meta model reference elements of the architecture model, which are expected to differ between the life cycle states. The variability model defines the required properties which might change individually during the vehicle's lifetime or throughout the life cycle states. The required properties are depicted either as requirements or as functions, components, and modules, which are necessary to fulfill the states' required properties. Thereby, elements of the product architecture model, which might change, are referenced by variation points. Possible realizations of these elements are depicted as variants of these variation points. Interdependencies between the variants are modelled according to product line engineering principles. The variability model is an optional part of our meta model because some architecture meta models already support variants.

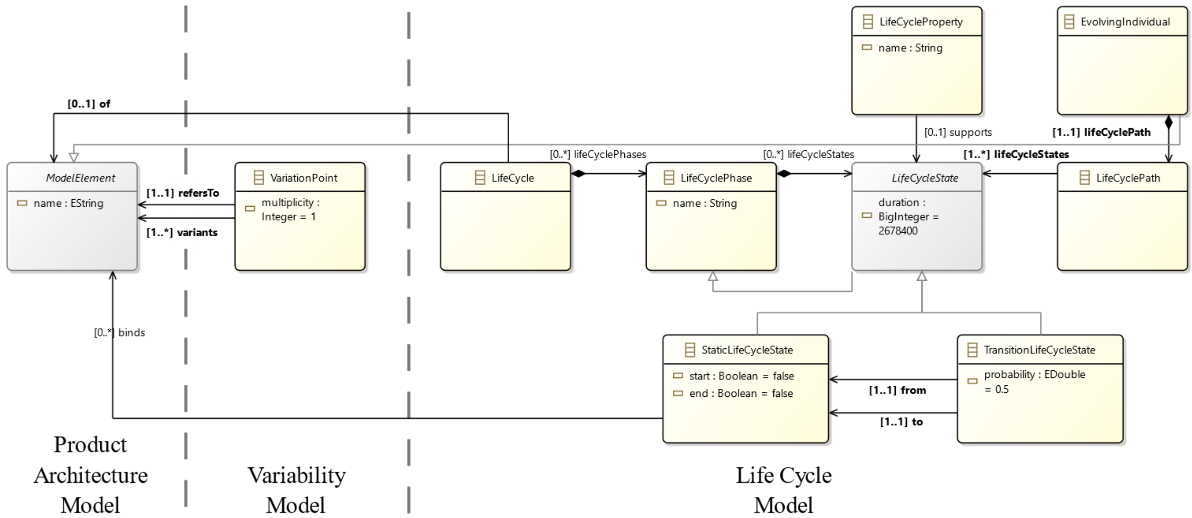


**Fig. 1.** The most important elements and attributes of the meta model with its three parts

In general, the variability model does not assign the variants to any specific life cycle state nor to any individual product. This is realized via the life cycle model. The life cycle model references the variants in the variability model and bundles them to consistent, static life cycle states. Static life cycle states describe a certain and fixed-in-time configuration of requirements, functions, and components, which are specific for this state. Yet, transitions between the static life cycle states might occur, which represent a dynamic state of product evolution (see Fig. 3). According to the definition of a life cycle state, such a transition is also a life cycle state. Thus, a transition life cycle state is additionally introduced, which describes the product's state while evolving from a previous static state to a next static state. Transition probabilities for the transition life cycle states allow to model the dependencies and underlaying logic, regarding which life cycle state might later be realized for the individuals. Thereby, transition probabilities are understood as in the Bayesian interpretation of probability. The transition probabilities are prior estimates of the proportion of products produced, which will take this transition (see [32]). LCE incorporates life cycle properties in early stages of design. As such, the prior estimates must build upon subjective beliefs or previous, yet not immediately transferrable knowledge. The prior estimates might thus stem for example from predecessor products, market studies, simulations, or personal experience of the product designers. They can even be expressed through more rough and uncertain probability measures like fuzzy set theory, possibility theory or Dempster Shafer evidence theory (see e.g., [33]). Probability distributions can then be derived from them.

Finally, life cycle properties are modelled qualitatively by the objective they aim to achieve. They are associated with life cycle states, in which they might provide a value by supporting or realizing the required properties therein. The association is then used in the methodology to determine and evaluate valuable life cycle properties (see section 3.2). The life cycle states, and their transitions form a Markov chain (see Fig. 3). Exemplary life cycles for individual products can be derived through Monte-Carlo-Simulation (see Fig. 4).

Overall, the three conceptual parts decouple the design and life cycle property decisions from the time and individual-focused perspective. This reduces complexity and enhances transparency as well as comprehensibility. The variability model for example depicts differences between the life cycle states in the product architecture's domain, while ignoring the time and individual-focused perspective. The life cycle states can be modelled without a full product architecture available. Yet, they can be easily associated with the respective requirements, functions or even components of a product architecture, if they are already present. Our meta model has been defined according to the MOF standard to allow for maximum interoperability with different product architecture models.

### 3.2 Methodology and Model Perspectives

The meta model's conceptual structure already helps in reducing complexity when dealing with individual life cycle paths. Yet, a methodology is necessary. It should describe how to setup a life cycle model from our meta model and how to use it to evaluate and determine the life cycle properties. Our proposed methodology is depicted in Fig. 2.

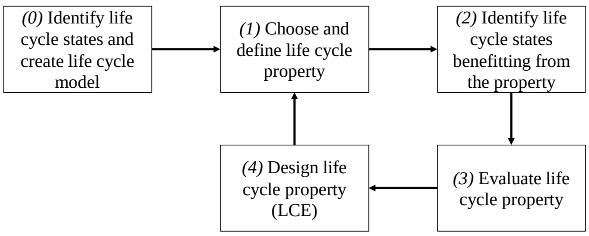


**Fig. 2.** Methodology to incorporate individual and divergent life cycle paths into LCE

Initially, the life cycle model must be setup. This is already a small subordinate methodology on its own. In a first step, the life cycle states are defined. For each life cycle phase, the product's stakeholders in this phase as well as their requested product properties are identified. The product properties are then aggregated, based on the situation in which they become relevant. These situations are the static life cycle states. Transitions between the life cycle states are determined, based on hypothetically feasible product evolutions. The transition probabilities are derived from previous products, market research or experience for example (see section 3.1). Finally, the life cycle model should be checked. The probability distribution over all life cycle states can be controlled to lay within the expected ranges, and individual life cycle paths can be investigated regarding their feasibility (see Fig. 4 and Fig. 7).

The life cycle model can then be used, to evaluate and determine the life cycle properties. Firstly, potential, beneficial life cycle properties for the product are identified. They can be derived for example from customer demands and market trends or the company's strategy. Subsequently, each potential life cycle property is associated with a set of life cycle states. These are the states, in which the life cycle property might deliver value. As such, each required property of each life cycle state is compared against the potential life cycle property. If the states' required properties are supported by the life cycle property, the state is associated with the life cycle property (see Fig. 4). Favorable technical implementations of the life cycle property become apparent.

Thirdly, the life cycle properties are evaluated. The probabilities that a life cycle state benefitting from the life cycle property is passed in an average, individual life cycle is calculated. This proxy for the value of a life cycle property helps in deciding to which extend the life cycle property should be incorporated. High probabilities hint towards a higher utilization of the designed properties. Low probabilities suggest that the life cycle property is only of value for a small portion of the individual products. Ultimately, the life cycle property can be designed into the product architecture using a suitable LCE methodology from literature. Thereby, knowledge regarding a beneficial design is already present from step (2). Furthermore, exemplary, individual life cycles and the probability distribution of the life cycle states can be used, to evaluate design solutions in this process. Consequently, the approach extends LCE: The meta model supplements existing product models to account for diverging life cycle paths and an associated methodology evaluates and determines valuable life cycle properties.

We supplement the methodology with three prototypical viewpoints of our models to reduce cognitive complexity. Perspective (1) depicts the potential life cycle states and their transition probabilities as product variability over time (see Fig. 3). It depicts different states and links them via the required properties to the product architecture. Thus, it helps to uncover possible variants in the product architecture and is suitable to design the life cycle model. This perspective is mainly employed in the initial step of the methodology as well as in step (2).

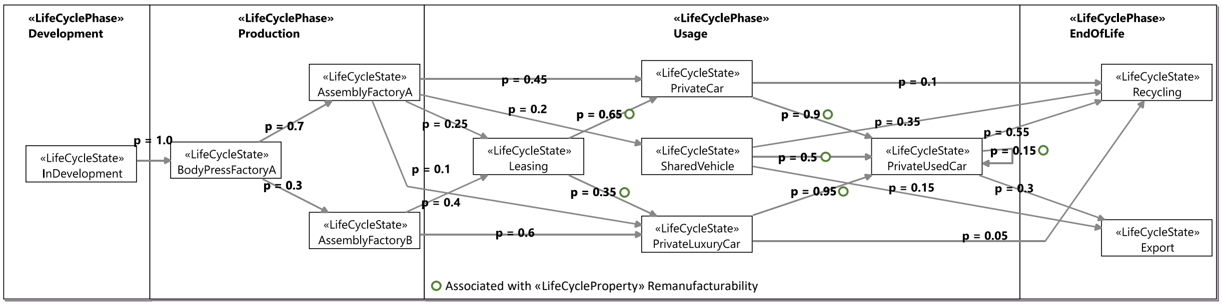


**Fig. 3.** Perspective (1) depicts the life cycle states and the transition probabilities between them (exemplary data from the evaluation)

The remaining perspectives (2) and (3) focus on the product to be developed. Perspective (2) depicts an exemplary life cycle path for a certain individual product over time (see Fig. 4). The probabilistic interdependencies are abstracted to infer implications towards the design decisions in step (4) of the methodology. Thereby, it is important to generate sufficient diverse and representative life cycles.

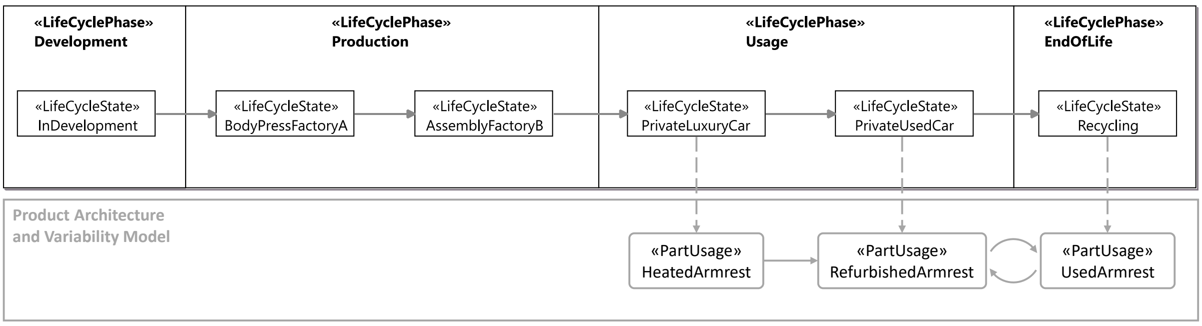


**Fig. 4.** Perspective (2) depicts exemplary life cycles (i.e., a specific, probable sequence of life cycle states) for individual products (exemplary data from the evaluation)

Perspective (3) is arranged around the product architecture. It depicts the product's requirements, functions and components with their different variants (see Fig. 5). They stem from the properties, required in the individual life cycle states. This perspective reveals points of potential change throughout the life cycle phases but ignores the interdependencies and sequence of life cycle states. It is used in step (4) of the methodology.

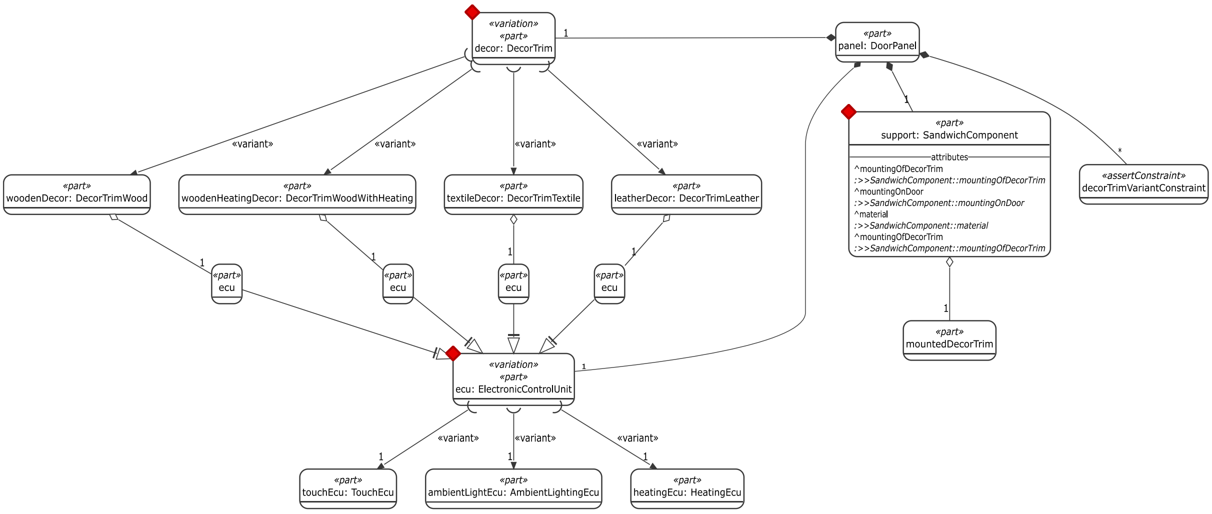


**Fig. 5.** Perspective (3) depicts the product architecture with its life cycle state induced variability (exemplary data from the evaluation); thereby, variability is marked with a red diamond

## 4 EVALUATION AND DISCUSSION OF CASE STUDY RESULTS

The evaluation of the meta model and the associated methodology has been conducted in the research project "futureFlexPro" [34]. The research project aimed for developing a flexible and sustainable smart door panel (SDP) for passenger cars. The meta model was implemented into an Eclipse modelling environment to employ the developed meta model and approach. The modelling environment features SysML v2 for the product architecture description. Overall, the software architecture of the modelling environment looked as follows (see Fig. 6): The information and knowledge about the required properties, life cycle states, life cycle properties and the product architecture were captured in a central product architecture model. The product architecture model is described through SysML v2 combined with our orthogonal life cycle model. Two add-ons were implemented to support the methodology's workflow. They are based on the data present in the product architecture model. A decision and evaluation layer displayed the perspectives, presented in section 3.

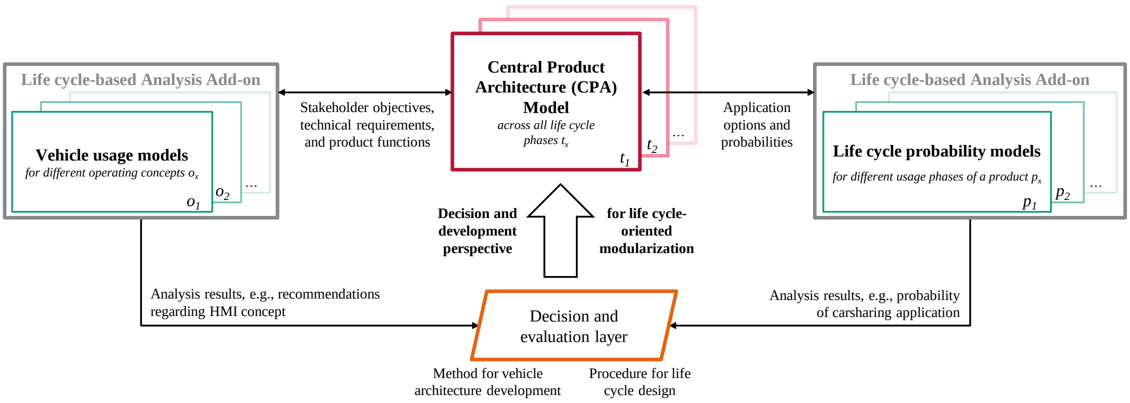


**Fig. 6.** The evaluation's software architecture for modelling and evaluating a smart door panel

Firstly, the life cycle model for the passenger car, its states and transitions were developed. The first add-on “Vehicle usage models” supported in this. A model of stakeholder objectives and derived product requirements was developed for two use cases: private car and carsharing car. Different stakeholder needs with respect to both use cases were identified and converted into required properties and assigned to life cycle states. For instance, an intuitive interface concept was requested by carsharing users, because reading user manuals is not feasible for time-based business models. Private car users in contrast were linked to shy tech and individualizable configurations. They can precisely adapt to their specific needs. As a car is either part of a shared fleet or used as a private car, different life cycle states were defined including the required properties of the stakeholders (see Fig. 3). Subsequently, the transition probabilities were derived based on different experts’ experience. At the same time, the life cycle model was associated with the product architecture. The need to exchange parts of interface components, for example when the vehicle is owned by a private user after being used for carsharing, became apparent.

The probability distributions for each life cycle state and each life cycle path were derived based on the life cycle model through the add-on “Life cycle probability models” (see Fig. 7). Potential beneficial life cycle properties regarding for example usability, reliability, performance, changeability, and remanufacturability were identified. They were associated with the life cycle states (see e.g., Fig. 4) and evaluated. It was found for example, that different SDP configurations throughout the life cycle of the same vehicle were required with a high probability (i.e., 89%). This in turn, pointed the designer towards the value of the life cycle properties remanufacturability and changeability for the SDP. They were realized for example for the décor material using magnetic coupling instead of simple adhesive joints. Thereby, perspective (3) helped to identify the points of change. Other recommendations derived concerned the placement of the electronic control units or necessary material characteristics of the SDP. Overall, our approach made it possible to analyze frequency, probability, and type of potential component exchanges, based on individual life cycle path estimations. Yet, we also found that modelling all possible life cycle states for the different stakeholders and linking them to the life cycle properties is cumbersome. Thus, our upcoming research regarding this topic, will address this issue, by extracting knowledge from previous linkages and automate the tool support.

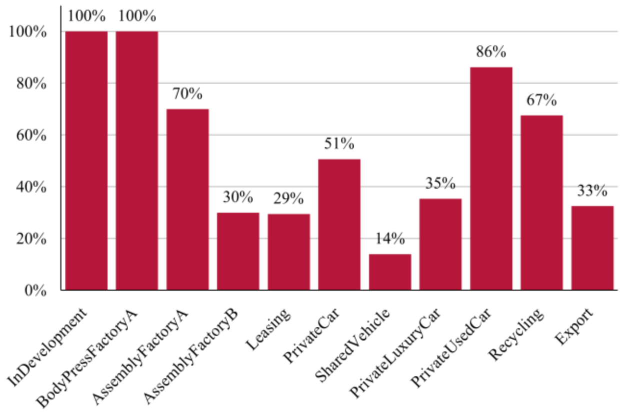


**Fig. 7.** Probabilities of the life cycle states, occurring at least once in an individual life cycle path

## 5 CONCLUSIONS

The goal of this paper is to add the consideration of individual life cycle paths to LCE, so that valuable life cycle properties for divergent life cycle paths can be evaluated and determined. We suggested a new meta model to describe individual life cycles in LCE. The meta model is complemented with a methodology. It describes how to use the meta model to evaluate and determine valuable life cycle properties and their implementation. Thereby, the approach supplements already existing LCE approaches. The meta model and the methodology can be used for different life cycle properties, given that a MSBE focused LCE approach for them already exists. In an exemplary evaluation case, our approach was applied to the design of a sustainable smart door panel. Suitable life cycle properties and their associated designs were evaluated and determined, with respect to the expected, individual life cycle paths.


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