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Designing a method-testbed for planning upgradeable mechatronic systems - an interview study

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ABSTRACT: In response to the environmental challenges posed by climate change and shortened product lifecycles, businesses must prioritize the design of sustainable and adaptable products. Upgradeable products present a viable solution to incorporate environmental impacts by maintaining technological relevance and addressing evolving user and customer needs, thus minimizing resource waste. To develop an effective design support for this, it is essential to create a specified method-testbed. This work employed a guideline-based expert study, applying qualitative content analysis to eight interviews. The analysis identified 38 factors crucial for supporting the development of sustainable, upgradeable mechatronic systems. These factors were consolidated into distinct objectives, resulting in 13 requirements that represent the method-testbed for a design support aimed at strategic upgrade planning.

KEYWORDS: upgrade, sustainability, design methodology, new product development

1. Environmental challenges and their need to design upgrades

Due to climate change and the increasing societal emphasis on sustainable practices, companies are being called upon to design products with foresight, adaptability, and, therefore, sustainability (Schuh et al., 2022; Tchertchian et al., 2009). The trend towards shorter product life cycles, which is associated with higher material consumption and enhanced waste production (Bakker et al., 2014; Huisman et al., 2012), increasingly threatens the goal of sustainable product development (Schuh et al., 2023). Product upgrades can counteract this issue and contribute to more sustainable product design (Khan & Wuest, 2018). By integrating new features over a product's lifespan through a modular architecture, upgrades can significantly extend its useful life, keeping it technologically up-to-date and adaptable to evolving customer and user needs (Schuh et al., 2023). Thus, the upgrade-induced extension of the time-in-use translates into the product lifecycle (Aziz et al., 2016). Developing methods for sustainable product design is a widely researched area. Numerous studies and design methods have been created and published (Aziz et al., 2016). However, little empirical research comprehensively addresses product upgrades (Xing et al., 2007). Existing research mostly focuses on generalized aspects, e.g., design for modularization, or does not incorporate concrete actionable design guidelines (Kuebler et al., 2023). Thus far, a systematic approach is lacking to ensure that potential upgrades are identified early on, enabling the proactive and therefore sustainable planning and modular development of such products. Design science has introduced a wide range of methods to support engineers in activities. However, the effective transfer of these methods into design practice remains a challenge. To enhance applicability and effectiveness, these methods require iterative validation before being integrated into practice (Marxen & Albers, 2012). In this context, the establishment of a validation framework for a design support being in development is particularly important, as it facilitates the systematic comparison of advancements across different development generations and their application in diverse studies. Consequently, a well-defined validation framework is required, which can be conceptualized as a method-testbed. Within design science, the structured interaction between objectives and requirements serves as the foundation of such a

testbed. According to Pohl (2010), an objective is described as an intentional description of a characteristic feature. Building on this, a requirement is a condition that the support must measurably fulfil in order to achieve the formulated objectives (Blessing & Chakrabarti, 2009; Pohl, 2010). By continuously aligning objectives and requirements, design support validation can be conducted iteratively, as proposed by Marxen and Albers (2012).
To develop a comprehensive design support and to provide measures for upgrade-oriented product planning, it is necessary to establish a method-testbed in this regard. Therefore, objectives as well as requirements as a metric must be derived for the iterative refinement of the design support. By conducting and analysing a semi-structured interview study with eight experts from industry and research, we narrowed down a system of objectives and synthesized a manageable set of 13 requirements, paving the way for later design of an upgrade-planning design support.

2. Research framework

2.1. Understanding sustainable product design

The concept of sustainability has become a central topic in the political discourse (Hauff, 2021). In addition, companies have made sustainability a key focus in product development, presenting them with ecological, economic, and social challenges that must be balanced. When resources are scarce and consumers are increasingly seeking environmentally friendly solutions, it is of paramount importance that products are designed in a sustainable manner throughout their entire life cycle (Schuh et al., 2023). The product life cycle is a conceptual framework that describes the various phases a product undergoes from its initial business idea to its disposal. The lifespan of products is limited (Lenk, 2000) and has been observed to undergo a constant shortening in recent years (Appenzeller, 2021; Braun et al., 2022; Huisman et al., 2012). There are multiple descriptions of the product life cycle, which vary in terms of their level of detail and their phasing. Nevertheless, the product development process (PDP) represents a pivotal point within the product life cycle representing the initial phase of a product life cycle (Albers & Gausemeier, 2012). It encompasses strategic planning, product development, and production system development. Despite the categorical delineation of these areas of responsibility, the chronological sequence of these phases is not necessarily strictly determined and may well overlap (Albers & Gausemeier, 2012). The product development phase offers significant potential for enhancing sustainability. In this context, it is essential to consider the sustainability-oriented concepts of eco-efficiency and eco-effectiveness. While the latter is initially concerned with the question of whether the appropriate goals and strategies are being pursued, the concept of eco-efficiency focuses on the effective utilization of resources to achieve these goals (Stahlmann & Clausen, 1999). Accordingly, a product may be defined as eco-efficient if it yields a favourable impact on the three fundamental dimensions of sustainability, namely ecology, economy, and social issues (Hauff, 2021). Becker (2018) defines an eco-efficient product as one that is economically competitive, improves quality of life by satisfying human needs, and consumes fewer resources than nature can regenerate in the same period of time. There are already various approaches to doing this, e.g., R-strategies. The name is derived from the same initial letter "R" of the various approaches. Examples include reuse, repair, refurbishing and remanufacturing. The objective of these approaches is to extend the lifespan of products and facilitate multiple subsequent life cycles, thereby fostering a circular economy (Acerbi et al., 2021; Reike et al., 2018). In addition, it is also possible to achieve these effects through upgrades. Upgrades facilitate the extension of product life cycles, significantly prolonging their use phase. Consequently, upgradeable products exhibit greater resource efficiency and are more sustainable than conventional alternatives (Schuh et al., 2023).

2.2. Designing upgradeable mechatronic systems - preliminary studies

It thus follows that product development should be linked to upgrades in terms of their potential to increase sustainability. Kuebler et al. (2023) identified success factors from literature that are relevant to the integration of hardware upgrades into the product life cycle. A two-stage design, comprising a systematic literature review and a preceding interview study, facilitated the illumination of the topic of future-robust product design. Upgrades and the relevance of the design of upgradeable mechatronic systems were identified as particularly salient areas of influence. From the market perspective, the fulfilment of customer needs and requirements was identified as a key influencing success factor for upgrades, particularly in the identification of upgrades. Regarding the design of upgrades, the design of upgrades for changeability was identified as a critical success factor at the system level (Kuebler et al., 2023). In order to implement this technically, a modular product architecture and standardization of interfaces are required. Standardized interfaces coupled with uncertain future conditions and changing customer requirements, represent a significant challenge. In particular, components that are subject to constant change can be designed variably through a modular architecture (Kuebler et al., 2024).

2.3. Understanding upgrades

In the field of linguistics, an upgrade is defined as "improving the quality or usefulness of a computer or machine" (Cambridge Dictionary, 2024). In the context of mechatronic systems, Albers et al. (2023), define an upgrade as a modification of a mechatronic system with the objective of enhancing user-friendliness and performance within its use phase, thereby extending its useful life while simultaneously addressing the evolving needs of supplier, user and customer. The implementation of the upgrades can be carried out by expert personnel, the manufacturer, or the user themselves, depending on the specific type of upgrade (Khan & Wuest, 2019). For this to be achieved, the product must be designed to be upgradeable from the outset. As upgrades interfere with the idea of developing and launching products at distinct times, the model of system generation engineering (SGE) allows to understand the interactions of upgrades between new system generations (see Fig. 1) (Albers et al., 2023).

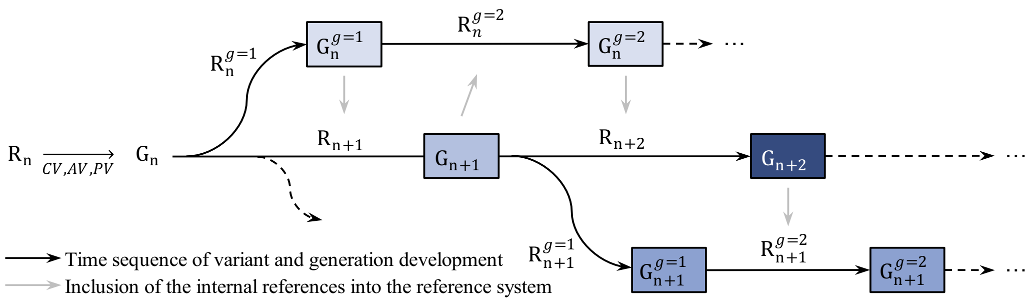

Figure 1. Interdependencies between different product generations when upgrading (Albers et al., 2023)

In the model of SGE, a new generation is developed by varying elements of an associated reference system in accordance with three variation principles (Albers & Rapp, 2022). Referring to upgrades, only individual subsystems are added or modified. Conversely, the reference system of a new upgrade variant is primarily comprised of elements from the previous generation. In addition, upgrades may be implemented at different time horizons. They are integrated throughout the entire use phase, and also continuously planned and designed in the product engineering process. Figure 1 illustrates that upgrade variants pertain to systems whose utilization is extended. In accordance with the definition of variants, product generation $G_{i=n}$ is modified to create upgrade generations g=1 and subsequently g=2, a process that extends to subsequent product generations. To do so, upgrades adapt a product to uncertain environmental changes and to benefit from new inventions (Albers et al., 2023). This adaptability allows for the continuous improvement of the product and its maintenance without the necessity of developing and launching entirely new product generations. Therefore, the products' resource efficiency increases, as less material and energy are required to manufacture new products. Furthermore, the dissemination of innovations can be accelerated as existing products can be upgraded quickly. As a result, customers and users benefit from a more affordable integration of new technologies, as they do not need to purchase a new product in order to benefit from new technology (Khan & Wuest, 2019).

3. Aim of research and research approach

The aim of this research is to contribute to the development of more sustainable products by designing a method-testbed for a design support on planning upgradeable mechatronic systems. As stated in 1, there is a lack of dedicated design support to facilitate the design of upgrades. Blessing and Chakrabarti (2009) highlight the importance of defining objectives and requirements as a foundation, while Marxen and Albers (2012) stress their role in iterative validation, to create such a design support. In order to do so, this research on the design of a method-testbed is guided by two questions:

What factors describe the objectives of a design support on upgradable mechatronic systems? What requirements can be derived from the system of objectives for the iterative and measurable evaluation of a suitable design support on planning upgradeable mechatronic systems?

To operationalize the research questions, an interview study was conducted, resulting in a synthesis of factors, objectives and requirements. The research procedure was structured in four phases (see Fig. 2).

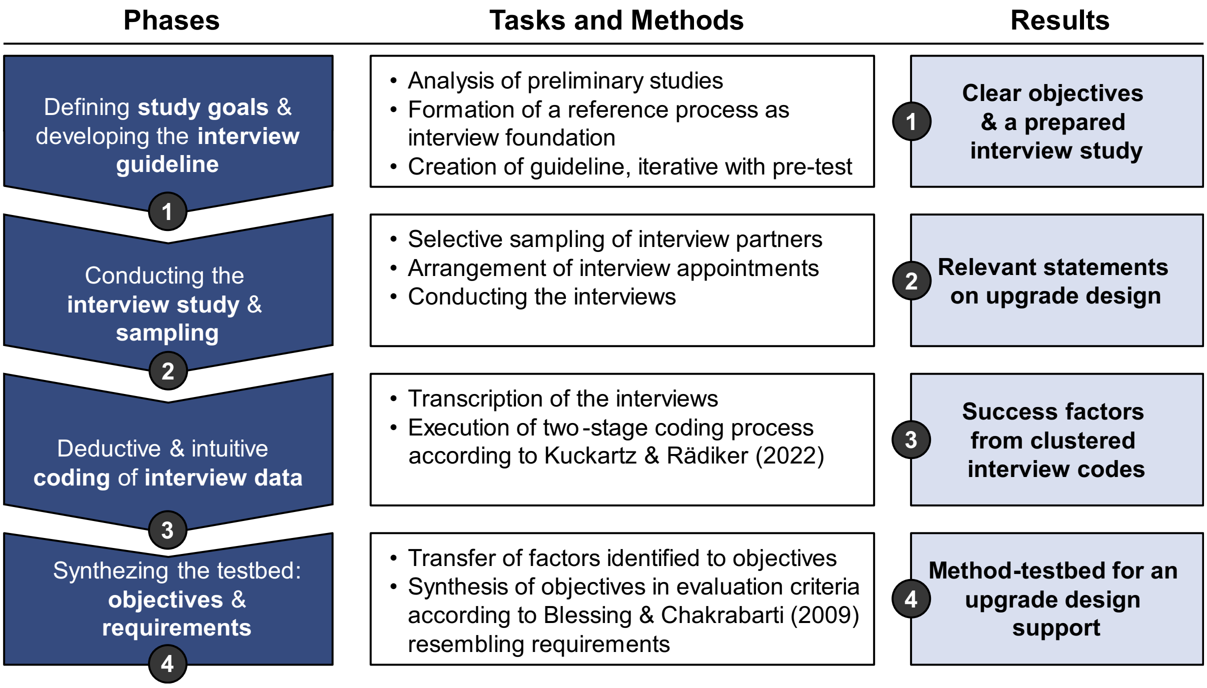

Figure 2. Research procedure containing phases, tasks and correlating results

In the first phase, study goals were defined, and an interview guideline was developed based on preliminary work (see 4.1). Given that product development is inherently a problem-solving process, the identified factors were categorized accordingly, aligned with development tasks, and integrated into the interview guideline. The guideline was validated through a pre-test. The second phase involved conducting eight interviews, with participants selected based on specific criteria (see 4.2). In the third phase, interview data were transcribed and coded using the methodology proposed by Kuckartz and Rädiker (2022). Finally, the fourth phase synthesized objectives and requirements for establishing a method-testbed to support the creation of a design support.

4. Conducting and evaluating the interview study

4.1. Development of the study goals and preparation of the interviews

Building upon the findings of Kuebler et al. (2023) (see 2.2) describing the phenomenon of *upgrades* rather than the embedding of these within a structured design process, these factors were clustered for the development of a design support testbed in a structured development process. As no implication should be made regarding a specific focus of the correlated product development process, the different interview findings need to be comparable. As product development can be viewed as a problem-solving process (Albers, 2010), the preliminary work (see 2.2) was clustered according to the *SPALTEN* problem-solving approach outlined by Albers et al. (2016). SPALTEN, a German acronym, is a structured seven-step approach with two recurring activities: **S**ituation analysis, **P**roblem containment, **A**lternative solutions, **L** – Selection of solutions, **T** – Consequence analysis, **E** – Make Decision and realization, and **N** – Recapitulate and Learn. The recurring activities adapt problem-solving team (**PST**) and **I**nformation **C**heck, ensuring team refinement and sufficiency checks after each step. (Albers et al., 2016) After mapping the factors, the understandability of the categories was enhanced for the interviews by referring to verbs describing the corresponding development activity: Identification, Planning, Design and process communication and control (see Fig. 3).

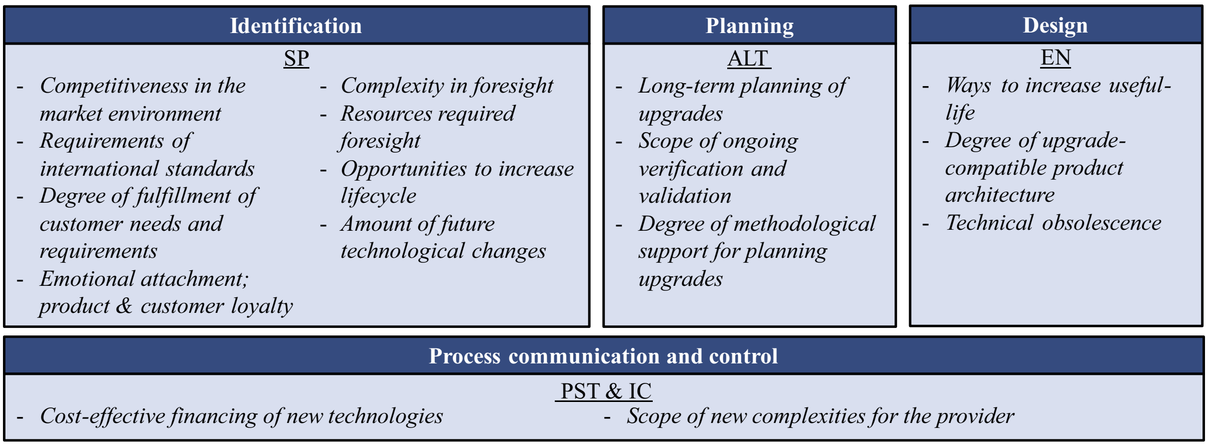

Figure 3. Upgrade influences according to Kuebler et al. (2023) categorized into product development activities embodied as a problem solving process

Based on this framework, a six-item interview guideline was developed to systematically gather relevant insights. The first item was implemented to ensure that the interviewees met the predefined sample criteria. To do so, their experience in the relevant areas of product development and strategic foresight, as well as their current employment, were assessed (I). To capture the initial perceptions of the interviewees without bias, the second item engaged them in a role-playing exercise. They were asked to describe their approach as lead of a development team in extending a products' life cycles. Building on this, they were then placed in a scenario where they had to guide the team in developing upgrades (II). Subsequently, the four categories outlined in Figure 3 - *identification* (III), *planning* (IV), *design* (V), and *process communication and control* (VI) - were used as a basis for exploring specific activities, applicable tools, and processes relevant to each category. The questions in the semi-structured interview blocks were based on the associated factors (see Fig. 3). To efficiently utilize the interviewees' time, two persons were working together to conduct the interviews with roles remaining consistent throughout the whole interview. One person marked already addressed influences or questions to keep track of open questions in the background, while the other remained the responsible interviewer. Therefore, a structured yet open-ended approach to capturing diverse insights on developing upgrades was ensured.

4.2. Characterization of the sample

To identify factors for developing a design support on upgradable mechatronic systems, eight semi-structured interviews were conducted via Microsoft Teams between June 23 and August 7, 2023, averaging 49 minutes each. Following a selective sampling approach, participants were chosen based on predefined criteria to ensure expertise in product development and strategic foresight (see Fig. 4).

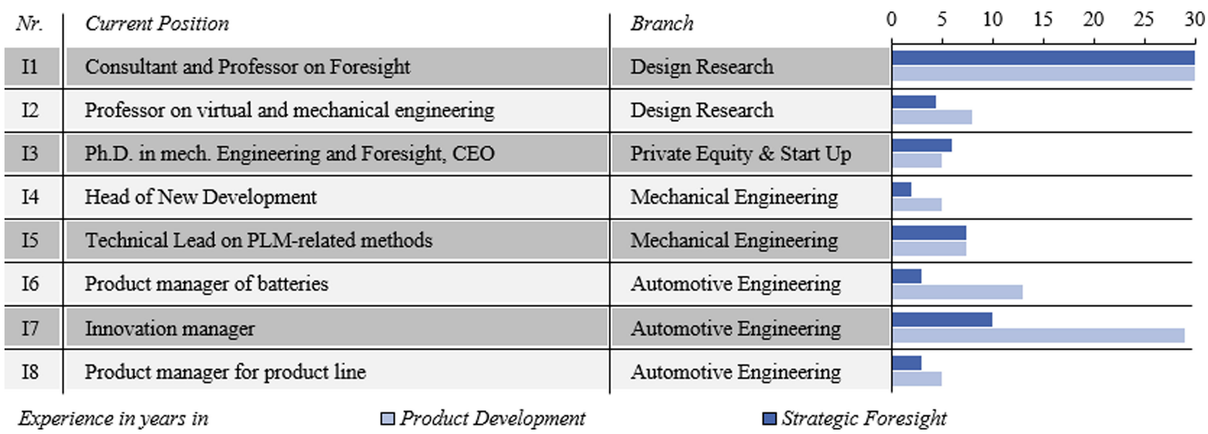

Figure 4. Demographics of interviewees with regard to experience on researched fields

The target group was deliberately narrow, prioritizing relevant knowledge over represent-ativeness. Invitations were sent individually to maintain confidentiality among participants. As a result of this procedure and the subsequent anonymization of the data during transcription, the impartiality of the responses provided by the interviewees was guaranteed, and the objectivity of the verbal data collected was enhanced (Doppler & Steffen, 2019). To prevent any inferences being drawn about the individuals based on the data collected, the names of the participants were anonymized. Only the position and branch in which the interviewee was employed at the time of the interview were provided (see Fig. 4). The eight interview participants can be assigned to four different industries. Although potential participants of both genders were requested, only male participants are represented in the final sample due to a lack of responses. With regards to strategic foresight, the participants have an average of around 8.25 years of experience, whereas the average experience in product development is almost 13 years. Overall, the majority of the participants' expertise can be found in product development. With a share of almost 61% of all years of experience, this area has the most experience.

4.3. Results of the interview study

The expert study was evaluated by using the qualitative content analysis proposed by Kuckartz and Rädiker (2022). In accordance with their process, the second step entails identifying deductive main categories that will serve as the foundation for the initial coding process. This entails utilizing the categories outlined in the guideline (Kuckartz & Rädiker, 2022). The transcripts of the interviews were subjected to two rounds of review, with a total of 414 text passages being coded in the MAXQDA 2020 software. In the initial coding phase, the text passages were allocated to the designated categories. Subsequently, multi-layered subcategories were formed within each main category, on the basis of which the second coding process was then carried out. In the event that an individual text passage had been previously coded in a manner that was deemed to be unsuitable, it was moved to a more suitable category. The 414 text passages were assigned to 78 categories in total. The four categories that had been derived from the guidelines, in addition to a category for the recording of demographic participant data, constituted the deductive category system. Based on the content of the aforementioned deductive categories, multi-layered subcategories were then formed that were thematically relevant. Figure 5 shows the deductive main categories and the inductively determined 17 first-order subcategories.

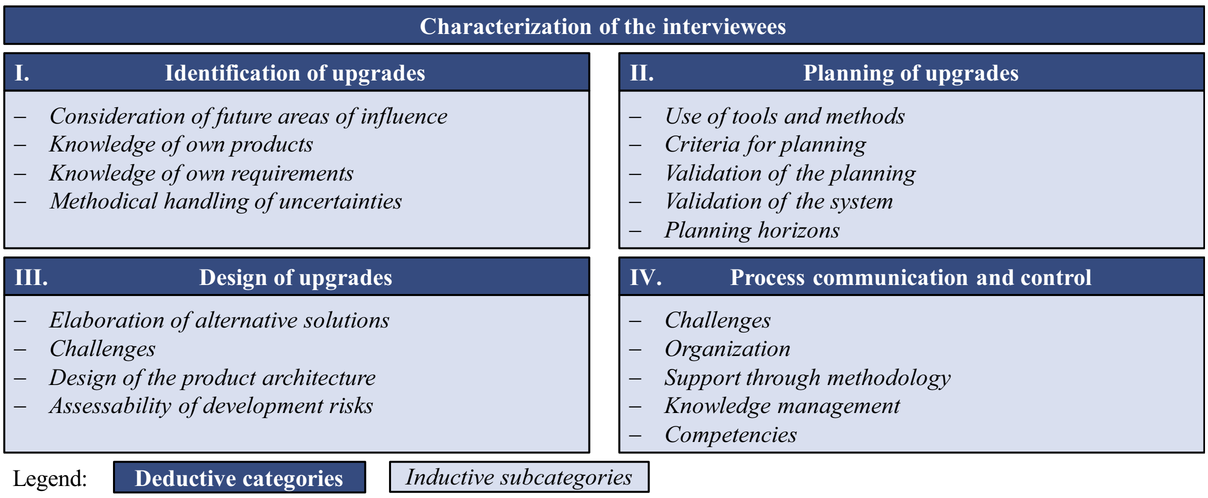

Figure 5. Deductive categories and formed inductive first-order subcategories

Regarding the *identification of upgrades,* twelve influencing factors were identified. The largest share, comprising six factors, was attributed to the *consideration of future areas of influence*. Four factors were attributed to the *methodical handling of uncertainties*. One factor could be derived from the statements regarding the company's knowledge of its own product and its own requirements. In particular, assistance in identifying prospective customer requirements pertinent to future products represents a pivotal influencing factor with regard to upgradeability (I6,8). I1, I2, I6, I7, and I8 explicitly highlight the importance of meeting customer needs. Consequently, an upgrade is only justifiable if the customer perceives a tangible benefit and if the necessity of the upgrade is evident (I1,2,3,6,7,8).

In regard to the *planning of upgrades*, seven factors were identified. I1 and I5 underscore the significance of roadmapping, particularly the formulation of system roadmaps to clarify interdependencies and create release schedules. Consequently, the extent to which existing tools can be integrated should be included

as a factor. Furthermore, the interview study identified three additional *criteria for planning*. It is necessary to examine the relevance of the upgrade in the planning process. This entails identifying critical failure points associated with non-implementation (I3) and anticipating technological advancements to ensure the product is designed for upgradeability (I6). Furthermore, it is essential to be able to accurately estimate the cost of the modifications to the system that are necessary for an upgrade at an early stage (I2,3). The technical implementation of the system, and the resulting interactions and dependencies, determine the extent of the difficulties associated with implementing an upgrade (I5). In cases where there are numerous interdependencies between two subsystems, the feasibility of upgrading both of them separately is significantly reduced (I1,5).
With respect to the *design of upgrades*, eight factors were identified. The capacity to abstract and modularize discrete levels or subsystems of a system in a targeted manner (I1,2,6) without introducing new dependencies was identified as a critical factor for the *design of the product architecture*. Accordingly, the boundaries of subsystems must be explicitly delineated and defined (I1,2,5,6,7). It is essential that interfaces are designed future-robust and compatibility (I2,4,5,6,7,8). Moreover, it is preferable to fulfil the requirements of users through the utilization of existing components and subsystems (I1). This is also beneficial for the commercialization of an upgrade, as it means less principal variation in the remaining subsystem (I3,4). Consequently, as the proportion of new development shrinks, the easier upgrades can be offered to the customer (I2). For this to be achieved, it is essential that the production system is compatible with the upgrade, without necessitating a significant adaptation effort (I3). The feasibility of utilizing existing resources is, therefore, another factor to be considered.
Ultimately, eleven factors were identified with respect to *process communication and control*. In particular, four factors were identified with regard to *support through methodology*. The tools, methods, and processes must be adapted to align with the requirements of the upgradeable product (I5). Methodological approaches that are currently in use are not employed due to the necessity of modifying them to a significant extent. Additionally, the utilization of unsuitable alternatives is observed due to the unavailability of suitable options. Accordingly, adaptability to the specific needs and circumstances is of paramount importance, as is the assurance of a continuous support process. Consequently, it is imperative that the individual steps be precisely coordinated (I5) and that an efficacious flow of information be ensured between the activities. A consistent approach that explicitly delineates the requisite activity at all times and ensures access to knowledge commensurate with the circumstances is of paramount importance (I1,2).

5. Method-Testbed for an approach to plan upgradeable mechatronic systems

As stated in section 1, a testbed for developing a design support consists of objectives and requirements. To specify support objectives on planning upgradeable mechatronic systems, the factors identified through the two-step coding process (see 4.3) were systematically merged.

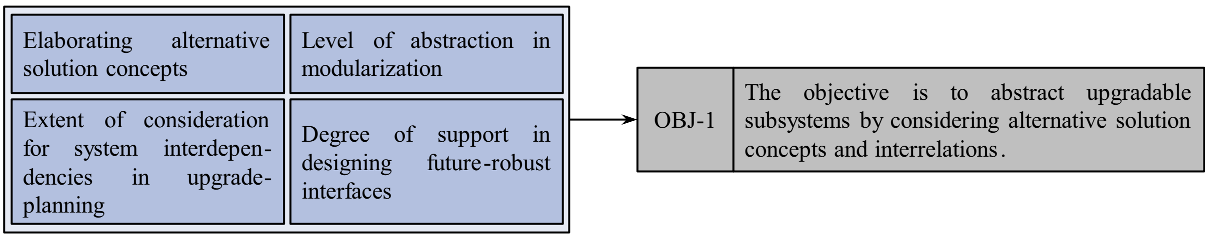

Figure 6. Process of merging factors into objectives using the example of objective No. 1 (OBJ-1)

The factors were clustered into their respective deductive categories and further organized into inductive subcategories to form specific objectives. This process ensured that each objective was grounded in the data obtained from the interviews. For instance, as illustrated in Figure 6, the derivation of Objective 1 demonstrates this methodology. Similar factors, shown on the left-hand side, were grouped based on the collective knowledge of the study participants. As can be seen, all four interview-based factors address an aspect of Design for modularization, yet with a different focus. In order to cope with them in an organized manner, the synthesized Objective No. 1 (OBJ-1) incorporates them holistically: future-robust interfaces and interdependencies get clustered to the differing abstraction levels by incorporating interrelations between alternative solutions. This process was applied to all nine objectives. The objectives serve solely as the foundation for developing the design support framework, not for its measured validation. To be able to evaluate the framework in a comparable manner, requirements (REQ) were derived in alignment with the design research methodology (DRM) proposed by Blessing and Chakrabarti (2009). DRM distinguishes between three types of evaluation, here referred to as requirements: *support*, *application* and *success*. The required *support (SUP)* of the design methodology is narrowed down by describing its functionality. *Application* requirements *(APP)* describe the setting and the surrounding in which the method can be used while *success* requirements *(SUC)* represent whether the expected impact of the design support is achieved. By analyzing the nine objectives, 13 requirements were synthesized into these three categories (see Tab. 1). In some cases, objectives were divided into multiple requirements to address distinct facets comprehensively (OBJ-1, OBJ-2, OBJ-6).

Table 1. Objectives (OBJ) and their related requirements (REQ) for a support on planning upgradeable mechatronic systems

OBJ	Objectives	REQ	Requirements
OBJ-1	The objective is to abstract upgradable subsystems by considering alternative solution concepts and interrelations.	SUC-1	The approach must facilitate the identification of future interactions between changing subsystems.
		SUC-2	The approach must enable the identification and exploration of alternative upgrade solutions.
OBJ-2	The objective is to make future technological developments, uncertain customer needs, and boundary conditions usable for identifying, planning, and designing strategic upgrades.	SUC-3	The approach must enable the identification of upgrades by exploring future technologies.
		SUC-4	The approach must enable the identification of upgrades by exploring future customer needs.
		SUC-5	The approach must enable the identification of upgrades by exploring future environmental factors.
OBJ-3	The objective is to support the effectiveness in evaluating upgrade development scopes and the associated development risks.	SUC-6	The approach must enable the effective evaluation and assessment of development risks and ensure the prioritization of individual development scopes.
OBJ-4	The objective is to maintain an overview of existing products and utilize the insights gained from them for future upgrades.	SUP-1	The approach must support the integration of knowledge gained.
OBJ-5	The objective is to always provide the user of the approach with suitable tools and the necessary knowledge for the corresponding step in the upgrade process.	SUP-2	The approach must support the utilization of generated environmental and product knowledge over the entire planning horizon.
OBJ-6	The objective is to open up existing structures and to encourage employees to develop their creative potential by fully integrating the approach.	SUP-3	The approach must support future-oriented thinking and facilitate the exploration of potential development paths.
		APP-1	The approach must establish trust and acceptance in its implementation and results.
OBJ-7	The objective is to ensure the traceability of the approach.	APP-2	The approach must be easy for the development team to follow, with clear, understandable steps.
OBJ-8	The objective is to establish an appropriate balance between effort and benefit.	APP-3	The approach must offer an appropriate cost-benefit ratio.
OBJ-9	The objective is to design the approach so that existing tools can be integrated and it remains applicable across various application contexts.	APP-4	The approach must enable the integration of existing product development tools and processes.

6. Implications for strategic upgrade planning in mechatronic systems

Reflecting on the interviews, it can be observed that there was a wide range of expertise among the eight participants. While this diversity was not intended to and does not allow to prioritize factors, it does indicate that a suitable sample was found. Considering the clusters found, the gained knowledge does not only employ insight into the whole upgrade design process, it can also be used to develop a wide range of supports varying from product planning to embodiment design. To make the results from the interviews tangible for developing a design support, it was essential to derive specific objectives. The transferability of these objectives for a wide range of design support methods is also given here. However, a dedicated transferability of the requirements other than upgrade planning to the subsequent development process is not possible, as they intent to measure upgrade planning assistance within success, support, and application. With these three measurement dimensions, the requirements allow to iteratively develop a design support for upgrade planning and to evaluate distinct areas of improvement. Initially, a first version of such a design support should be created based on the objectives and requirements, followed by multiple, iterative evaluation studies based on the requirements. Since this work focuses on upgrade planning, further studies should also synthesize requirements for the subsequent upgrade development process in appropriate segments. Only a continuous development process, encompassing both strategic product planning and product development, can enable the successful implementation of upgrades. Beyond this potential for future research, the approach of this work can also be used to develop a testbed for other design support method strategies. The applicability of this method-testbed, as well as its transferability to other cases, will be the subject of future research.

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