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Future-robust product design - validating influencing factors on upgradeable mechatronic systems

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Abstract

This paper examines upgradability through modular product design, aiming to extend lifecycles and promote cross-generational use. It builds up on a preceding work, a systematic literature- review identifying four fields of action in future-robust product design. The paper itself contains an in-depth interview study with 17 experts from industry and research to validate and expand the literature-based fields of action. The results provide insights into the application and employment of future-robust product design, with a focus on adaptable product architectures.

Keywords: upgrade, design methodology, design research, sustainable design, modularisation

1. Introduction - need for upgradeable mechatronic systems

The rapid pace of technological advancement, coupled with the increasing demand for individualised and digitised products (ElMaraghy *et al.*, 2013; Vogel and Hultin, 2018), has led to shorter lifecycles for both technology and products. In the face of climate change challenges, new design methodologies are required which prioritize sustainability (Ceschin and Gaziulusoy, 2016). One such concept addressing the need for individualization and sustainability is upgradability. Modular product design emerges as a promising supportive framework to achieve this goal. (Chierici and Copani, 2016; Schuh *et al.*, 2023) Given the volatile market, the product environment is constantly changing. In order to meet changing customer needs for as long as possible and to ensure sustainability, modular products must be adaptable throughout their life cycle (Mörtl, 2003; Greve *et al.*, 2021). This adaptability can be realized through a flexible product architecture that enables the replacement of physical components (Umeda *et al.*, 2005; Schuh *et al.*, 2023). This replacement allows the integration of new technologies into existing products, enabling them to meet changing customer requirements.

In a previous work, Kuebler *et al.* (2023), various influencing factors were categorised into four fields of action for the future- and change-robust design of modular products, with upgradeable mechatronic systems representing the most promising. In order to enhance and validate this previous work, this paper conducted an in-depth interview study with 17 experts.

2. State of the art

In today's evolving markets, there is a growing demand for upgradeable products that meet the ever-changing needs of consumers, while also addressing sustainability (Khan and Wuest, 2019; Schuh *et al.*, 2023). Upgradable products, designed with modularity principles, can change its functionality and features through pre-considered upgrades. (Umeda *et al.*, 2005; Chierici and Copani, 2016) This evolution of a system in generations can be described by three variation principles. (Albers *et al.*, 2023)

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The next section introduces sustainability and how it relates to modular product design. Furthermore, the architecture of modular products and its variation principles for development are then explained before a review of previous work closes this section.

Sustainability is divided into three dimensions in literature: Social, economic and ecologic sustainability. The three dimensions are equally important and should be considered together. (Geissdoerfer *et al.*, 2017) To achieve defined sustainability goals, three fundamental political and social strategies have been identified: sufficiency, consistency and efficiency. The sufficiency strategy aims to reduce resource consumption through voluntary changes in societal behaviour. (Huber, 2000) The efficiency strategy supports the use of environmentally friendly technologies, to reduce resource consumption and waste. (Vezzoli and Manzini, 2008) Consistency addresses either minimal interference within closed technological cycles or alignment with natural metabolic processes, allowing for smooth integration even in the presence of large volumes. (Huber, 2000)

Modular and upgradable products reduce the amount of material used, as the life of a system is prolonged with only minor changes to new material due to upgrades. They therefore use the strategy of sufficiency and consistency to meet the ecological dimension of sustainability. In addition, these systems can be economically relevant due to their modularity, thus reducing the variety of parts. These advantages of modular and upgradable products are based on their specific product architecture. (Schuh *et al.*, 2023). The product architecture consists of functional elements, physical components and the specification of interfaces between interacting physical components (Ulrich, 1995). The product architecture describes the functional and physical product structure as well as their interconnectedness (Krause and Gebhardt, 2018). The physical separation in modular products largely enables independent development and interchangeability of the individual modules (Ulrich, 1995). Specific modules can be added or omitted to enhance functionality and address individual customer and user needs (Khan and Wuest, 2018). This adaptability of hardware components is necessary for upgrades. (Schuh *et al.*, 2023; Umeda *et al.*, 2005; Chierici and Copani, 2016) As the upgrades are implemented during the product's time in use, they have already been considered in the product development phase (Mörtl, 2003; Albers *et al.*, 2023). Albers *et al.* (2023) definition of upgrades summarises these key aspects (see Fig. 1):

> *An upgrade is a modification of a mechatronic system that extends the usability or performance of the product to meet uncertain or changing supplier, customer, and user needs and boundary conditions by improving or extending functions of the system through an adaptively designed product architecture by adding or changing subsystems within the use phase. These upgrades are provided to customers and users through a suitable business model. (Albers et al., 2023)*

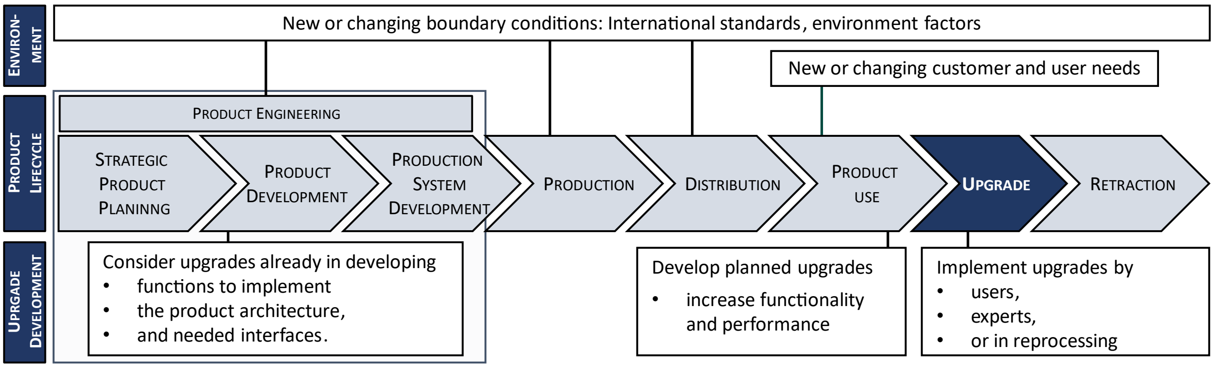

Figure 1. Interrelations of upgrades during a product lifecycle, using the understanding of the product lifecycle according to Albers and Gausemeier (2012)

To consider upgrades during product development, different methods can be used to create a picture of future needs and the environment (Thümmel *et al.*, 2022). Foresight is crucial in the early stage of product development, as most product properties are defined (Cooper and Kleinschmidt, 1993). Product development is described by the Model of SGE - System Generation Engineering, which describes the development of systems through varying references with three principles (Albers and Rapp, 2022). A new product's development is based on a reference system, which integrates one or more elements from

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previous or competitor systems (Albers *et al.*, 2019). These reference system elements are incorporated into the new product without modification, apart from interfaces, as carryover variation, altered in shape as attribute variation or modified in functionality as principal variation (Albers and Rapp, 2022).

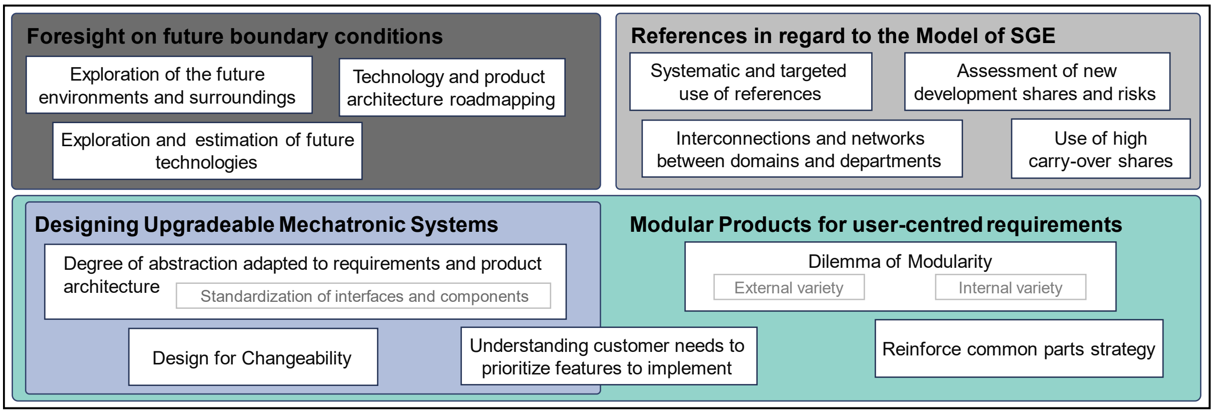

Figure 2. Fields of action in future-robust product design according to Kuebler et al. (2023)

Some of the findings listed are compiled in a previous work. Based on a systematic literature research, four fields of action for future-robust product design were identified in Kuebler *et al.* (2023). The first field of action *Foresight on future boundary conditions* supports the importance of using foresight when developing a modular, upgradable system. The focus of this foresight field is on environmental scenarios, future customer and product requirements in order to assess the future requirements that the product will have to meet. The second field of action is *References in regard to the Model of SGE*. The field contains factors that influence conscious SGE, communication within the company, using reference products, external diversity and decisions in the early phase, since they have a significant influence on development risk. As mentioned earlier, the field *Modular Products for user-centered requirements* is essential in ensuring adaptability throughout the product lifecycle. Immediate and corelated factors are influencing the interface, internal and external diversity and the product architecture with its granularity. Adaptability is in turn addressed by *Designing Upgradeable Mechatronic Systems* (see Fig. 2). It includes factors related to interface standardisation, level of flexibility and changeability of the system. These factors can be used to outline the product requirements and challenges associated with system upgradability. (Kuebler *et al.*, 2023)

3. Research profile

Upgradeable mechatronic systems combine sustainability with evolving needs of the market, while addressing individualisation through the use of a modular architecture. To develop a suitable design support for these long-lasting products, the relevant influences need to be fully understood. Kuebler *et al.* (2023), published in ICED23, provides four fields of action in this matter based on a literature review. It identifies the interconnections and dependencies of relevant factors and related methods. To validate the fields of action and to collect new factors with practical relevance, a semi-structured interview study with industry-experts was conducted. Therefore, the study addresses the following research questions:

1. To what extent can the literature-based influencing factors on future-robust modular products be validated by experts from industrial practice?
2. How can the overview of fields of action be expanded to include findings from practice?

3.1. Methodology of research and interview study profile

To validate and enhance the literature-based four fields of action an interview study was conducted, transcribed and evaluated. Due to the small possible sample size, interviewees were selected using a targeted approach to ensure expertise in the subject matter. This approach included specific criteria in terms of engineering or management expertise and experience. Individuals were required to have worked in Modular Product Development or Strategic Foresight for at least three years. In addition, the interviewees had to work in an industry with high turnover, e.g. mechanical, medical or automotive

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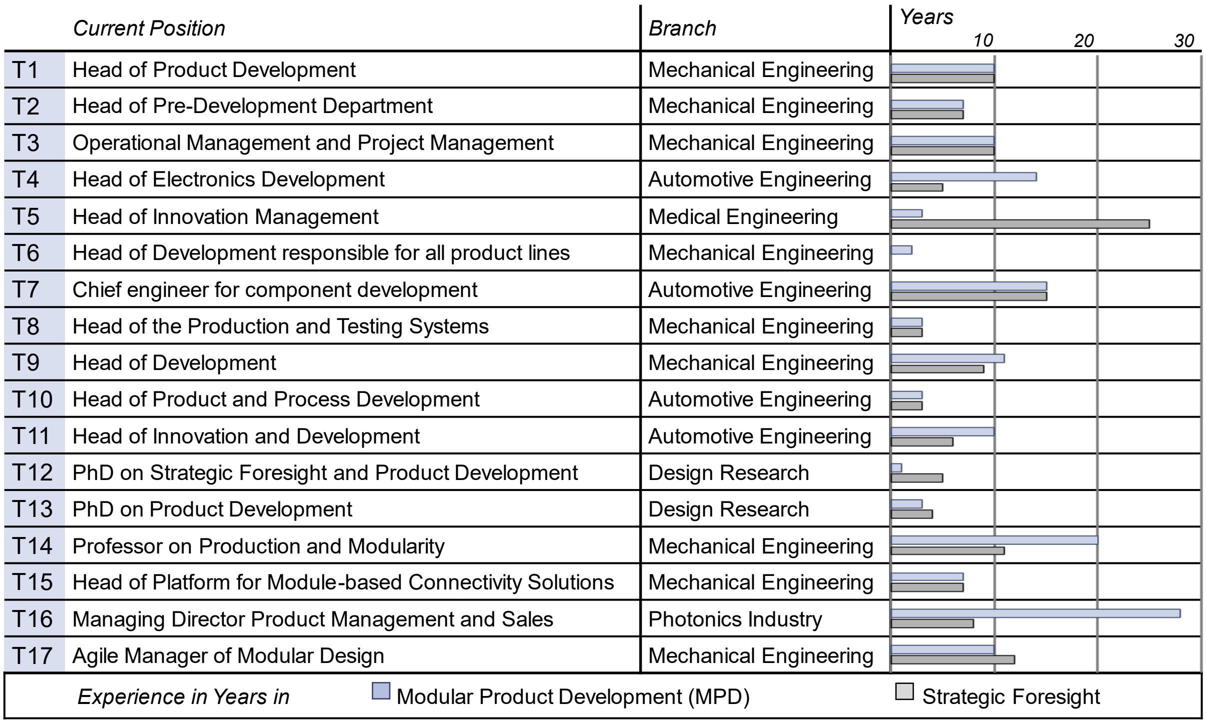
engineering. To enable a holistic view, individuals from related fields of research were also considered. According to Steffen and Doppler (2019), defining criteria before contact ensures credibility of the results and guarantees the most relevant and heterogeneous findings possible. 26 individuals, already known by the researchers, were contacted based on the stated criteria, 17 agreed to an interview. In addition to the pre-established criteria, a semi-structured interview guideline was developed, for a flexible yet structured interview process. All interviews were based on the same set of questions related to the four fields of action. In addition to the core questions, pre-developed supplementary questions were asked depending on the individual answers. The starting questions of the interview dealt with the field of activity and the company's industry in order to draw out the contrast of the sample. At the beginning of each interview section, a definition of each topic was given, such as modular product development, SGE, future robustness, strategic foresight and upgradability. This increased the validity of the statements by creating a common basic understanding (Steffen and Doppler, 2019). The questions were asked as openly and standardized as possible and could be answered through personal experience. The 17 interviews were held via video conferencing through Zoom, with an average duration of 37 minutes. All participants consented to recording their interviews, which were subsequently anonymised and transcribed. The demographics of the respondents were established through introductory questions. Eleven of the contestants work in the mechanical engineering sector, while three are employed in the automotive industry. Several interviewees are responsible for the development of mechatronic products, even though mechanical engineering was classified as branch. Their roles range from development manager to project manager, head of department and postdoctoral researcher. Figure 3 displays the demographics of the interviewees.



	Current Position	*Branch*
T1	Head of Product Development	Mechanical Engineering
T2	Head of Pre-Development Department	Mechanical Engineering
T3	Operational Management and Project Management	Mechanical Engineering
T4	Head of Electronics Development	Automotive Engineering
T5	Head of Innovation Management	Medical Engineering
T6	Head of Development responsible for all product lines	Mechanical Engineering
T7	Chief engineer for component development	Automotive Engineering
T8	Head of the Production and Testing Systems	Mechanical Engineering
T9	Head of Development	Mechanical Engineering
T10	Head of Product and Process Development	Automotive Engineering
T11	Head of Innovation and Development	Automotive Engineering
T12	PhD on Strategic Foresight and Product Development	Design Research
T13	PhD on Product Development	Design Research
T14	Professor on Production and Modularity	Mechanical Engineering
T15	Head of Platform for Module-based Connectivity Solutions	Mechanical Engineering
T16	Managing Director Product Management and Sales	Photonics Industry
T17	Agile Manager of Modular Design	Mechanical Engineering

Figure 3. Demographics of interviewees with regard to experience on researched fields

The *analysis of the transcriptions* relied on the qualitative content analysis method according to Mayring (2015), which is recognised as a mixed methods approach. A code system based on the interview guidelines was created to evaluate the transcriptions. Each of the four fields of action, together with the demographics, constitute the four deductive superordinate categories. In the analysis of the interviews, inductive sub-categories were formed. The analysis was carried out using the MAXQDA analysis software. A total of 698 passages were coded after reviewing the interviews twice. In the first cycle, passages were assigned to the superordinate categories, the fields of action, and later to more specific categories based on those in Figure 2. In the second iteration, the passages were directly assigned to the

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refined categories. Subsequently, the passages underwent screening and further categorisation or adjustments. A total of 689 passages were categorised into 129 distinct categories. The numerous categories simplified the summarisation of the respondents' statements.

4. Results - validated and extended fields of action

The interviews enabled the four fields of action to be verified and expanded by industry-relevant factors. To simplify the presentation of these results, the inductive categories were clustered into the four deductive fields of action. The resulting clusters are *highlighted* and explained by characteristic codes.

4.1. Foresight on future boundary conditions - challenges and methods

The literature-based factors *future customers*, *environmental scenarios*, and *architecture requirements* were addressed, along with new factors *challenges of the application*, *type*, and *time horizon* of foresight. During the interviews, participants highlighted *various motivations* for performing foresight. Six participants emphasised the importance of megatrends for future market predictions. T3, T9, and T10 delved into the analysis of political changes, while seven participants underscored the significance of the market views in, emphasizing the essentiality of analysing competitors and customer needs. T15 and T16 underlined the importance of forecasting technology. Several companies recognized sustainability as a significant area of interest (T1, T3, T7, T8, T10, T11, T16).

Companies acknowledge *challenges of implementing foresight* in product development but recognize its relevance *and benefits*. T3 prioritises the need for foresight, while highlighting uncertainty of exploring future trends and the early phase of developing products. Consequently, the company should increase its agility to enable quick responses (T10). But developing modular products requires foresight since the product architecture is established early and remains consistent across multiple products (T15). To develop trust in the results of foresight, the involvement of employees is crucial (T12). The benefits of foresight include a more intelligent allocation and prioritisation of resources, improving the future-robustness of products (T13, T15, T17). However, suppliers need less foresight due to narrow customer requirements, limited development time and low margins (T10, T11). Organising the vast amount of information necessary for accurate and beneficial foresight presents a significant challenge, requiring structured organisation and documentation (T13). Other challenges are the associated costs and effort (T10, T11, T12, T13) since the costs for foresight can only be saved in the long term (T13). In numerous companies, the lack of a systematic approach to foresight poses a challenge (T3, T4, T6, T10).

The *foresight time horizon* varies between companies, with a long-term approach suggested for products with extended development times and lifespans (T7, T10). Product categories such as standard products and products influenced by market volatility have a shorter horizon (T1, T3). According to T15, a longer time horizon leads to better company preparation. T17 recommends thinking two to three product generations ahead to create effective roadmaps. The time horizon is influenced by the product category, with standard products having a reduced foresight horizon (T1). However, certain components dealing with major developments must be carefully considered (T5). Several *foresight methods* were mentioned in the interviews. Discussions with departments and experts such as sales and interdisciplinary committees are important for gaining insight into market developments (T3, T8, T9, T16). T16 organizes future workshops to envision the company's current and target positions in the coming years. Companies use tools like *Product of the Future* to visualise future product concepts (T3, T4, T7) and *Picture of the Future* to illustrate developments in major areas.

In the early phase of product development, *product architecture requirements* are identified based on environmental and technological foresight. These requirements are then evaluated against various criteria, including product range expansion, planned sales, and compatibility with the product portfolio (T2, T9). T9 and T12 highlight the difficulty of estimating sales and customers. T9 further suggests that the process must determine which properties to include in the basic version and which are customer-specific solutions. The initial release should address 80 % of customer needs (T9). Furthermore, effective product architecture development is facilitated by knowledge of component interactions, organised requirements and scope analysis (T17).

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4.2. References in regard to the Model of SGE - System Generation Engineering - Engineering, knowledge management, structure, and organisation

The literature-based factor *communication* was extended by general *organisation within the company*. The factors *reference products* and *carryover shares* are a part of the new field *knowledge management* and *development based on SGE*.

In *product development based on SGE* T4 distinguishes between development projects with new technology and carryover variations, e.g. model maintenance. T3 and T4 aim for a high proportion of carryovers to achieve high quality and low risk due to proven design. T1 and T3 address risk assessment, while T1 finds an optimistic evaluation of the first development generation helpful in order to give new ideas a chance. In the case of novel developments, immature developments can be shifted to the next generation (T9). The transition between generations can be challenging (T2, T10), particularly in removing old generations from the market (T10). Functions with unclear necessity and low implementation time should be developed in short-term if the market demands them (T16, T13). Hereby roadmaps are useful to plan technology, products, and resources (T15). Technology roadmaps provide upcoming functions and their market launch (T6, T10, T11). Product roadmaps organise development goals (T11, T13) based on time and development effort. T17 recommends developing the architecture and the product in parallel. Stakeholder workshops can be a useful tool for roadmap planning (T16). The recommended time horizon for roadmaps is two to three generations (T2, T17). The roadmaps are based on the results of the first field of action foresight (T3, T6, T17). However, synchronizing development cycles presents challenges (T15). T16 says that customers prefer not to have an entirely new product with each generation, making a high carryover share or upgrades favourable options. One challenge is downward compatibility desired by the market so elderly product components can continue to be replaced (T9, T13). Most companies use their own predecessor product as a reference system element (T1, T2, T3, T5, T9). At the beginning, dos and don'ts of the previous generation are derived (T1, T3) and complaints are considered (T2, T9, T11). T9 finds it easier to develop based on own references, as they can orientate themselves on the architecture of the reference system. The unique selling point and best sales argument is incorporated as far as possible (T1, T3, T4).

Knowledge management is crucial in modular product development, especially in abstract modelling of requirements and product architecture. It becomes even more important during long development periods to ensure that valuable knowledge is retained (T9). Organizing knowledge in different hierarchies helps to provide an overview and efficiency, focusing on important information first before diving into more detailed knowledge (T13, T15). Relevant information includes technology roadmaps (T4), requirements management (T4), general development reports (T4), information on critical components (T9), documentation of the product architecture development process (T9, T12, T17), learnings (T13, T15) and risk assessment (T1) of multiple product generations.

The *organization of a company* has a significant impact on product development and employee performance. The use of agile methodologies, such as the sprint system, can lead to a lean product architecture systematic, but excessive checks and approvals should be avoided (T14). However, the implementation of agile practices may be hindered by excessive checks and approvals (T14). To ensure successful agile product architecture development, methods should be simple and intuitive, allowing developers to rely on their expertise and experience (T17). T17 recommends to develop the architecture and the product as well as their roadmaps in parallel (T15). Empowering teams with autonomy and self-organization enables them to contribute intrinsically to the overall architecture and drive agile development (T17). Teams should consist of a *stable core of experts* who are well-rehearsed, and a changing part, for new impulses (T15). T17 notes that cross-functional teams, containing diverse skills and experiences, are essential for pursuing common project goals.

4.3. Modular products for user-centred requirements - product types, product development and range of variants, future robustness, process methods

The interviews provided insights into the *development of the modular product architecture* and product development. The *range of variants* and *future robustness* with adaptability was discussed in the

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literature and the interviews. Added factors are the *types* and *goals* of architecture development, the *development methods with module roadmaps*.

The companies differ in the type and implementation of *modular product architecture development to ensure* future robustness. Some opt for a less modular approach, relying on *meta construction kits* (T10) based on guidelines and different predeveloped technologies (T13) that are later easily integrated into products based on market demands. T7 blends different standardisation strategies in construction kits and scale product size. Another approach involves developing a basic product version and then creating different variants from it (T16). Modular development is beneficial for a small number of products of the same variant (T14) and when the application range of the architecture is wide (T7).

Balancing *external diversity with internal diversity* in product development presents a challenge for companies, necessitating the formulation of strategies. To limit this dilemma the high variance can be supported by IT (T9) and the number of variants should be reduced by clear limitation guidelines (T9, T15, T14) and restricted costumer options (T14). An authorization procedure for special variants also protects the architecture. T10 also mentions not always aiming for the best solution but finding solutions that align with the product architecture. Overall, modular product development serves different purposes. The mentioned objectives reveal that many of these objectives are interconnected (see Fig. 4).

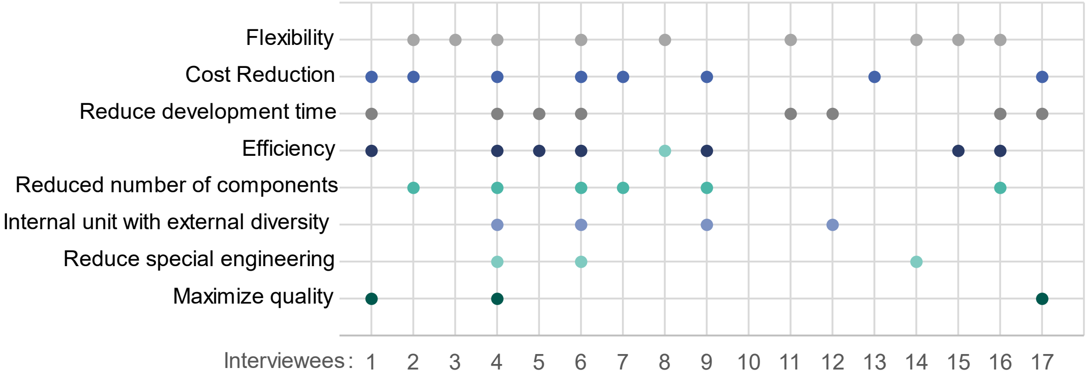

Figure 4. Objectives of modular product development mentioned in the interviews

As stated in field of action 4.2, T17 recommends developing architecture and product in parallel, starting with abstract descriptions and transferring them to concrete terms. This process should be done iteratively and in short cycles (T17). However, the product architecture typically endures for two to three generations beyond the module (T17). It is difficult to define a clear lifetime as it is constantly evolving due to volatile markets (T17). To build a stable architecture, visualising the product architecture during the development helps to improve understanding. *Increasing the lifespan and robustness of a product* requires a focus on future-orientation for the product and its architecture. *Future robustness* is seen as a key objective in designing modular product architecture (T8, T12). Supportive factors are development and business planning (T3) along with foresight (T9). Communication is essential for future robustness, with problem recognition and implementation at the lower level and organization at the upper level (T9). Assessing future-robustness in the development process is considered important but challenging in practice due to the vague nature of future research (T5, T14). External experts or representatives from specialized areas can be consulted for evaluation, while minimizing the influence of management (T7, T14). Evaluation methods of future-robustness include identifying critical components (T12), utility analysis (T14), analysing expansion options and used technology (T4, T15), and environment scenarios (T3, T6, T17). The *process of product architecture development* varies among the companies, involving various departments at the beginning. During the initial stages, it is crucial to allocate significant resources and effort to systematise and structure the architecture (T10, T14). T4's approach suggests developing individual products first and then building the product architecture based on similarities. T3 initiates the development process by using the largest quantities and most extreme variant to build the product architecture. Afterward, the most extreme variant undergoes testing, which verifies all the other variants (T3). Continuous evaluation is needed to meet internal and market requirements (T15, T17). It is also helpful (T15) to assign responsibility for developing specific modules (T15). Designing a modular product architecture poses challenges, such as

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verifying conformity to standards that slow response times, identifying weak points for future-robustness (T4), and managing the pressure to bring products to market quickly (T17). Companies are also faced with cost pressure (T12), long architecture development times (T12, T14, T16) and uncertain future conditions (T5). Oversizing or higher costs can result from standardization (T4, T10).

4.4. Designing upgradable mechatronic system - granularity, standardisation, advantages and challenges

The literature-based factors *standardisation strategies* and *standardised interfaces* were confirmed. *Flexibility* was added based on *granularity* of product architectures in relation to *design for changeability* and *degree of abstraction* adapted to requirements and architecture. Furthermore, *benefits and challenges of upgrades* as well as possible *product categories for upgrades* were scrutinised.

In upgradable system design, *standardisation* is crucial. Standardisation can be achieved by using standardised materials and portfolios with different characteristics (T1), which reinforces the common parts strategy. Standardisation benefits development time (T4) and employees, as most components and structures are familiar, resulting in a quicker engineering process. It is established through regulations such as design guidelines (T7), in-house standards (T10, T11) and specifications (T3, T16). For instance, upgrade regulations include combinability in the product architecture (T16). Standardisation allows more identical parts to be used, resulting in benneficial bundled purchasing (T2) and customer recognition through component similarity (T7). Overall, standardisation plays a decisive role in enabling the downstream exchange of parts. Therefore, *Standardising interfaces* is particularly important (T6, T8, T15), especially for control, pneumatics, electrics, and mechanics (T8). According to T13, interfaces should be influenced by as few dynamics as possible. Standardised interfaces enable system expandability, targeted module development, flexibility, and combinability (T1, T2). However, there is a danger of integrating unnecessary interfaces to maximise system flexibility (T3). Dimensioning the interfaces is complex, with a risk of insufficient support for new functions (T17).

Granularity or the extent of modularity becomes pivotal in upgradable systems. The required variance in the architecture determines the necessary granularity (T4). Rapidly changing components can be built in as variable interfaces, allowing for flexibility (T15). Furthermore, planning for additional installation space facilitates easy component and supplier changes (T3). However, achieving flexibility through overengineering can result in excess installation space, empty channels, and additional power capacity (T4). This approach may not be suitable for low-cost mass products, due to cost efficiency and space optimization (T4).

Upgradable products offer sustainability (T1) and other *benefits* but also present *challenges*. Modular product architecture and standardized interfaces are key enablers of upgradable design. However, the expansion of features is currently focused on software and not well integrated into the hardware (T2, T8). Upgrades can enhance functionality, accommodate additional performance and exciting features (T1, T4, T13). This provides flexibility to adapt to market changes and enables companies to provide *Prio B features* (T12, T14). Upgradability and related service can strengthen customer loyalty (T3). However, *challenges* include the need for forward planning to anticipate trends and future customer demands (T5, T8, T17). T5 and T14 criticise the feasibility of forecasting features, as the future cannot be predicted and no concrete information is provided (T5, T14). Additionally, there is increased complexity and cost associated with needed *interchangeability* for future upgrade considerations (T10, T17). T13 mentions that it may be essential to adopt a less efficient design to create additional space to facilitate upgrades. In industries with short product life cycles and disposable products, upgrades may not be practical (T1, T3, T10, T11). Furthermore, the ability to upgrade depends on the specific industry (T15), with sectors like health and safety requiring safe upgrades carried out by trained staff (T7, T15).

5. Limitations of the conducted interview study

Participant selection involved selective sampling, considering expertise in product development and strategic foresight. Fig. 3 depicts the resulting participant composition, showcasing a broad spectrum of expertise. The data relies solely on participants' self-assessment. Despite this variance, the sample selection guaranteed sufficient expertise for the interview study. Discrepancies in experience are

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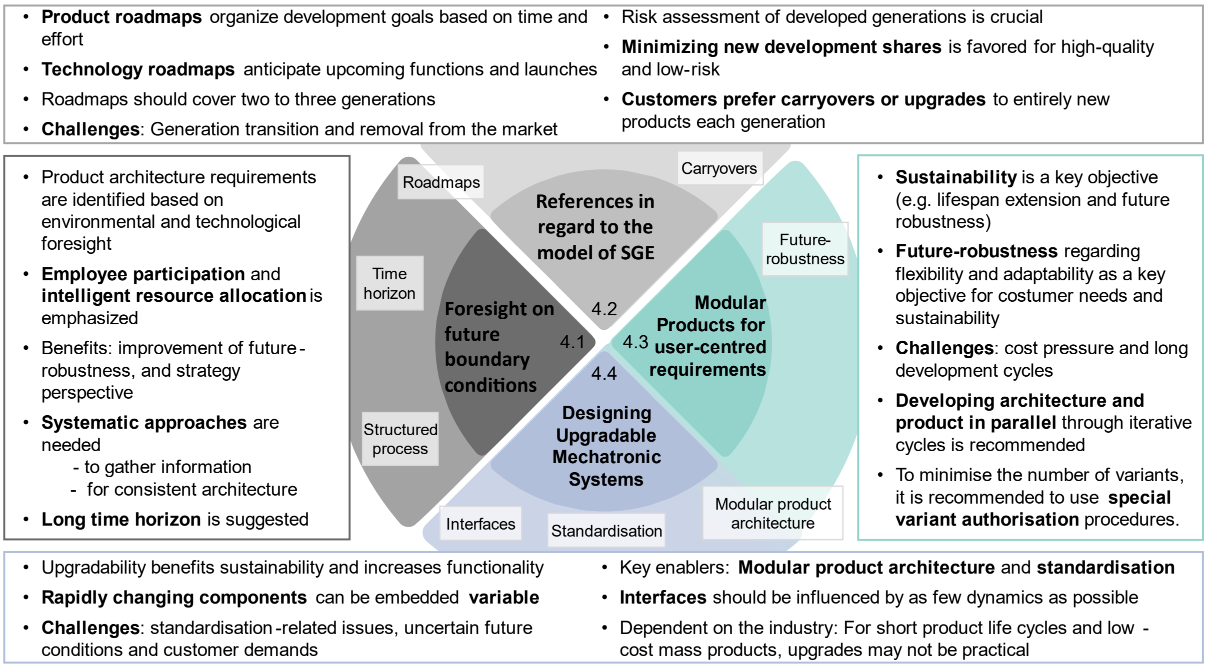
attributable to variations in age, indicating a potential correlation between earlier career entry or higher age and work experience. A semi-structured guideline was developed for data collection, ensuring comprehensive information retrieval consistently across all interviews. Following the framework concept proposed by Gläser and Laudel (2010), the interview guidelines served as a flexible structure that allowed for adaptation to the participants' responses while maintaining procedural consistency. Stringent efforts were invested in formulating questions to guarantee uniformity in participant interactions and to ensure repeatability and therefore reliability of the interviews. In order to prevent possible biases, care was taken to allow interviewees the freedom to express themselves without undue influence. The comprehensive description, adhering to Mayring (2015) procedural guidelines, prioritized both implementation objectivity and evaluation objectivity, ensuring a meticulous balance between methodological rigor and participant autonomy.

6. Conclusion and outlook

This paper explores the concept of upgradability in mechatronic systems in response to the gap between an evolving landscape of technological, individualized innovation and growing demand for sustainability. It is found that there is need for new design methodologies on upgradeability which prioritize sustainability amidst shorter product lifecycles. The work builds on previous research and validates and extends the literature-based fields of action for future- and change-robust modular products via a comprehensive interview study involving 17 experts from industry and research. The synthesized insights are encapsulated in Figure 5.



- **Product roadmaps** organize development goals based on time and effort
- **Technology roadmaps** anticipate upcoming functions and launches
- Roadmaps should cover two to three generations
- **Challenges**: Generation transition and removal from the market
- Risk assessment of developed generations is crucial
- **Minimizing new development shares** is favored for high-quality and low-risk
- **Customers prefer carryovers or upgrades** to entirely new products each generation

- Product architecture requirements are identified based on environmental and technological foresight
- **Employee participation** and **intelligent resource allocation** is emphasized
- Benefits: improvement of future-robustness, and strategy perspective
- **Systematic approaches** are needed
    - to gather information
    - for consistent architecture
- **Long time horizon** is suggested

- **Sustainability** is a key objective (e.g. lifespan extension and future robustness)
- **Future-robustness** regarding flexibility and adaptability as a key objective for costumer needs and sustainability
- **Challenges**: cost pressure and long development cycles
- **Developing architecture and product in parallel** through iterative cycles is recommended
- To minimise the number of variants, it is recommended to use **special variant authorisation** procedures.

- Upgradability benefits sustainability and increases functionality
- **Rapidly changing components** can be embedded **variable**
- **Challenges**: standardisation-related issues, uncertain future conditions and customer demands
- Key enablers: **Modular product architecture** and **standardisation**
- **Interfaces** should be influenced by as few dynamics as possible
- Dependent on the industry: For short product life cycles and low-cost mass products, upgrades may not be practical

Figure 5. Key Findings in four fields of action conducted in the interview study

For subsequent research, the paper emphasizes developing a design support framework for upgrades. This entails harnessing insights from the current and prior work to articulate clear objectives and requirements for the design support. The subsequent phase involves precisely defining the design support itself. The integration of hardware upgrades with software updates is essential for today's mechatronic products. The intended design support aims to promote adaptability and longevity by enabling the seamless and planned replacement of physical components. This, in turn, facilitates the integration of emerging technologies, ensuring products remain responsive to evolving customer needs. Updates in particular should be discussed further in this context, as this paper focuses on upgrades and therefore only deals with the software aspect secondarily. In conclusion, this paper not only offers an overview of influencing factors in modular product design but also sets the stage to support design in navigating the challenges of rapidly changing markets and their customer and user needs.

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