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Addressing Circularity Strategies by Reconfiguring Smart Products during Their Lifecycle

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Abstract: Considering circularity aspects during the engineering of smart products implies a significantly increased complexity of engineering processes. Especially technical reconfiguration of smart products, offered as services in availability-oriented business models, enables the integration of circular economy aspects in sustainable products and lifecycles, through realizing several aspects of the 9R strategies. This paper introduces an analysis of interdependencies between 9R strategies potential reconfiguration options, technical characteristics of smart products, different maturity levels of smart product and abilities for circularity. Partial engineering models managed in different product lifecycle management systems provide a technical basis for systematization and evaluation of circular abilities of reconfigurable smart products in different lifecycle phases. The approach aims to improve circularity-related decision making in systems engineering processes in the early development phases and during the reconfiguration of smart products during utilization phase. An industrial use case considering a microelectronic-centered smart product used in e-mobility solutions validates the approach.

Keywords: 9R Strategies; Product Engineering; Product Lifecycle Management; Reconfiguration; Smart Products; Sustainability Strategies

1 INTRODUCTION

Sustainability has become a key concern in many industries, including product development [1]. Companies are increasingly aware of the importance of incorporating sustainability principles into their product development processes to minimize environmental impact and meet evolving customer expectations [2]. Products and how they are used have changed dramatically in a short time. This includes the sharp and fast rise in new technologies as well as a change in consumer behavior, which is reflected in greater individualization of products, greater demand for quality and an expansion of product functions [3]. Traditional product life cycles are changing, meaning premature product obsolescence occurs in addition to shortening useful product lifetime. As a result, products are pushed into the end-of-life phase early and often unnecessarily. In recent years, there has been a growing emphasis on developing smart products and product service systems that not only provide innovative solutions but also address sustainability concerns [4]. The development of smart products and product service systems presents new challenges in terms of sustainability [5]. These challenges arise from the increasing complexity of smart products, which integrate physical and digital components [6], as well as from the need for circular economy (CE) strategies that extend the lifecycle of products [7]. The attribute of reconfiguring smart products and product service systems in the context of the CE is a topic of growing importance [2]. To address these challenges, companies need to adopt new business models and strategies that enable the reconfiguration of smart products and product service systems in a sustainable manner. One approach is to shift from a traditional ownership model to a product-service system model [8, 9], where customers pay for the service or function provided by the product rather than owning the product itself. This model encourages longer product lifecycles and facilitates reconfiguration and upgrades to extend the usefulness of the product. Another crucial aspect of reconfiguring smart products in a CE is designing for reusability and upgradability [10]. This involves incorporating modular design principles, standardized components, and easy disassembly to facilitate component reuse and replacement [11]. Furthermore, designing products for upgradability allows for easy integration of new technological advancements, extending the product's lifespan and reducing electronic waste. By considering these factors during the product development process, companies can create smart products that are not only innovative and functional, but also sustainable. Approaches and procedures for implementing CE strategies with reconfiguration in SP have not yet been sufficiently described. Therefore, This paper aims to open opportunities and challenges for reconfiguring smart products with the inclusion of sustainable strategies at various points in the product life cycle.

2 STATE OF RESEARCH AND TECHNOLOGY

2.1 Circular Economy, Sustainability Strategies and Circularity

Sustainability attempts to form a balanced approach by shifting the dimensions of economy, ecology and society. The aim is to create value without restricting future generations. To incorporate sustainability and channel it into perspectives, goals and phases, the CE model is a suitable system. CE is a model that aims to derive business opportunities from leveraging circularity. However, CE strategies are challenging to define, as research has no uniform definition. There is also the opinion that more than one definition is achievable [12]. CE strategies can simultaneously improve multiple dimensions of sustainability by integrating different stakeholders' needs and creating value through resource conservation. Several approaches exist to categorize these strategies [13]. One such approach divides them into perspectives of strategies for slowing down, narrowing or closing the material loops [14]. Other definitions of CE strategies have a broader perspective on outcomes and focus on processes and outputs that address ecosystem functions and human wellbeing [15]. CE is not an end in itself [16], and it is not necessarily sustainable [17].

To draw a more general conclusion from the CE strategies and objectives, the following assumptions are relevant to this paper. Circular strategies need new business models that support their commercialization [18, 19]. In addition, lifecycle approaches need to be implemented that shift business models to a service-oriented perspective [14, 18]. Sustainability research results in new requirements (or stricter versions of existing requirements) that must be implemented in engineering. Design strategies such as design for long-life products, design for product-life extension or design for a technological cycle must be implemented and strengthened [14]. On the other hand, a business model must be linked to this to be able to commercialize the additional benefits. Designers and engineers must define new attributes that enable products to fulfill circular functions to meet these strategies [20]. However, established CE models still need to integrate established engineering methodologies and guidelines [21]. CE methods are mainly focused on material loops and their circularity in production.

2.2 Smart Products and Reconfiguration

Smart products represent a profound product design and functionality evolution, including technological advances in connectivity, intelligence and autonomy [6]. These products, characterized by their ability to collect, analyze and utilize data, have revolutionized various industries by offering personalized services, enhancing user experiences, and optimizing their performance. A key feature of smart products is their ability to continuously adapt and improve, using their embedded sensors and data analytics capabilities to gain real-time insights into user behavior, environmental conditions and usage patterns [2, 22]. This phase represents a dynamic period where the product interacts with its environment, adapting and responding to evolving circumstances. Smart products excel in optimizing resource efficiency, minimizing waste, and prolonging functional lifespan, aligning with the CE's principles. Reconfiguration emerges as a critical aspect of smart products, enabling them to adapt to changing requirements and preferences [23]. Defined as modifying existing product configurations to fulfill new needs, reconfiguration can manifest in various forms, ranging from general technical improvements to individual runtime enhancements [24]. This so-called smart reconfiguration combines the capabilities of smart products with the flexibility to adjust and evolve over time [25]. The resulting versatility enables smart products to remain relevant and effective in dynamic environments, catering to diverse user demands and preferences.

When developing smart products, everyone involved, e.g., development engineers, must think about the context of how products will be used throughout their life cycle [26]. This includes planning for potential future requirements starting from the early development phase to ensure the product can react to changing conditions during its use phase. In addition to the technical perspective, economic considerations also play a role in being able to change the business model in a resilient manner. These considerations must be anchored and considered in the development process through methods and guidelines. The factors can be summarized with the term "VUCA world", an acronym introduced in the 1990s by the United States Army which describes the possible challenges in a multilateral world through the terms volatility, uncertainty, complexity and ambiguity. Through reconfiguration, it is possible to react to the VUCA factors later in the product life cycle, adapt products and business models and thus enable products or product life cycle for resilience. The large number and diversity of goals for reconfiguring smart products require a more detailed consideration. The following goals are most frequently mentioned in the literature:

- Adaptability and expandability: Smart products must react to changes in the environment as well as to changing user requirements. Part of this goal can be changes to existing features or the enhancement of functions.
- Customization and personalized services: Smart products can analyze user behavior. On this basis, these products can be customized to individual people. As a result, individualized and personalized smart products can have a higher value for the user.
- Longevity and efficiency: The adaptability of smart products means that, on the one hand, their useful life can be extended or made more efficient and, on the other hand, products can be used for longer, which corresponds to an increase in their service life.

Several aspects have to be addressed during product development for dynamically reconfigurable smart products. Procedures and methods need to incorporate and focus on these properties. However, no established approaches currently cover, for example, design for reconfiguration for dynamic reconfiguration in the use phase [6].

3 SUPPORTING CIRCULAR ECONOMY STRATEGIES BY RECONFIGURATION

The 9R strategies arise from the perspective of the CE business model. R strategies are needed to identify value retention across life cycle phases and actors [20]. These strategies can be subdivided as the objectives can be projected to different product levels or product life cycle phases [27]. The 9R strategies range from R0 Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle to R9 Recover [28, 29]. Strategies R0 to R2 aim to minimize or reduce the use of raw materials before the economic cycle or production begins [30]. This can be achieved by removing the need for specific products or components, as their functions are fulfilled elsewhere. In addition, raw material consumption is reduced by increasing production efficiency or intensifying product use. Consequently, an equivalent customer benefit can be provided with fewer raw materials.

Strategies from R3 to R7 focus on keeping product parts in the economic cycle [30]. If the reuse of product components is no longer possible, strategies R8 and R9 attempt to at least keep the raw materials in the cycle or minimize waste. When introducing CE principles during the life cycle of an existing product during its utilization phase, strategies R3 through R7 offer the most significant potential for improvement. Additionally, product reconfiguration can offer benefits such as added value at the functional level. R strategies that can be applied at this level are R0 to R2. For this reason, reconfiguration should offer the opportunity to address R-strategies before the business cycle by changing the product in the usage phase. In this way, additional functionalities that would otherwise have to be provided by other products and intensification of product use can keep the product in the economic cycle or the use phase for longer.

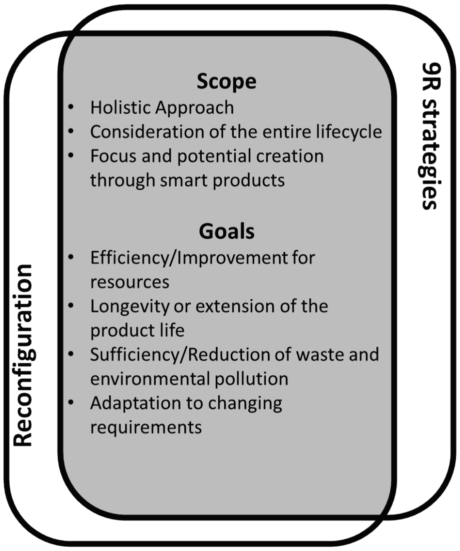

Figure 1 Common scope and goals of 9R strategies and circular product reconfiguration

Suppose the target dimensions of product reconfiguration and the 9R strategies are analyzed for generic overlaps in engineering tasks. In that case, similarities can be identified (Fig. 1). Both the reconfiguration of smart products and the 9R strategies aim to improve energy efficiency. Reconfiguration can help optimize energy consumption by deactivating functions when they are not needed or using more energy-efficient components. Both approaches aim to reduce the amount of waste and environmental impact. Reconfiguration can help extend product life and thus reduce the need for new production and disposal. The reconfiguration of smart products and the 9R strategies aim to optimize the use of resources, be it through the reuse of materials or the more efficient use of energy and other resources. Both approaches address the need to adapt products to changing requirements, whether by adapting functions, adding new features or changing design elements. In summary, the concept of reconfiguration, which also encompasses the objectives of the 9R strategies, can also be described as circular reconfiguration. Overall, there are significant similarities and overlaps between the goals of reconfiguring smart products and the 9R strategies, particularly regarding resource efficiency, waste reduction and adaptability. However, there are also differences in focus and approaches, particularly regarding the product life cycle and material use. While the 9R strategies strongly focus on the reduction, reuse and recycling of materials, the reconfiguration of smart products concentrates more on using existing resources and extending the service life of products. The 9R strategies often refer to early phases in the implementation and the emergence of the technical implementation to activate R3 to R7 in the use phase, for example. Circular reconfiguration can precisely solve this problem by implementing the potential of refurbishment or repair, among other things, in the utilization phase.

Existing approaches either do not consider reconfiguration as a potential for 9R strategies or only marginally [14, 20, 31-33], are mainly concerned with production and the reconfiguration of manufacturing machines, which is not generally transferable to smart products [34-36], or only consider the 9R strategies (R8 and R) for materialities [13, 21, 37, 38].

4 CIRCULAR RECONFIGURATION DESIGN DIMENSIONS

A smart product goes through various phases of the product life cycle. The segmentation is important because it examines the effects of and through the reconfiguration. Fig. 2 shows examples of different stages of the product life cycle. The approach of a circular reconfiguration is explicitly highlighted.

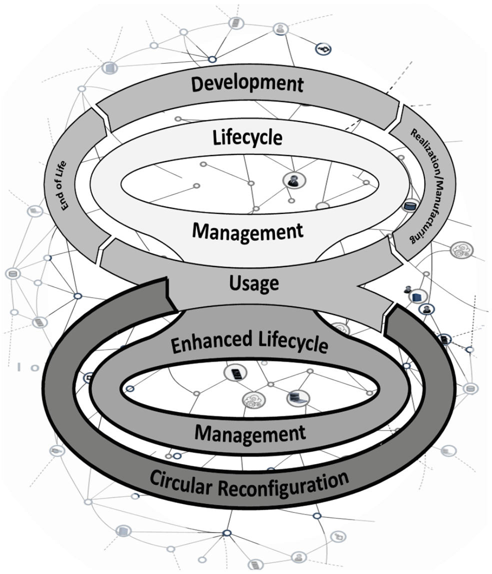

Figure 2 Smart product lifecycle with a focus on circular reconfiguration and enhanced lifecycle management

From a technical perspective, these can be divided into the following phases: strategic planning, development, realization/production, use, end of life cycle. This categorization is very general and can also be subdivided differently. Each phase has characteristics that are either reflected in the smart product or must be considered during its development. To be able to focus on circular reconfiguration, an extension of the life cycle phases is recommended. Either the utilization phase can be extended to include reconfiguration or, as in this case, a separate section can be created. The circular reconfiguration process is initiated in the utilization phase. In the next step, the actual circular reconfiguration process is carried out after triggering. This includes a separate product development process that covers the requirements and functions right down to the physical parts and sub-products. In the next step, the existing product is reconfigured digitally and/or physically, depending on the type of reconfiguration. This process can be referred to as the remanufacturing phase. After complete and successful reconfiguration, the product is back in the utilization phase. Each of these phases brings with it different challenges, requirements, and opportunities from a technical perspective in connection with reconfiguration. Business models that already consider the economic benefits of reconfiguration must be included as early as the strategic planning stage. The circular reconfiguration of smart products only makes sense for companies and organizations if added value can be created at an economic level. In the following, eight different design dimensions are discussed, which significantly influence circular reconfiguration.

4.1 Continuous vs a Priori Reconfiguration Option Development and Validation

The development and validation of reconfiguration options can be classified as continuous or a priory. Both possibilities have opportunities but also challenges that need to be considered. The a priori reconfiguration option development and validation enables operators to plan the product's behavior in advance, i.e. during the use phase and to take foreseeable conditions into account [10]. It allows precise adjustments to be made to the product right from the start to ensure optimum performance. This influence can increase efficiency through better utilization of resources and smooth (functional) product changes without constantly relying on and reacting to real-time data. Costs can also be better controlled through a priori reconfiguration development and validation, as development and implementation can be planned in advance. Potentially costly changes during operation can thus be avoided. Disadvantages include a lack of flexibility and limited adaptability during the utilization phase. A priori reconfigurations are fixed and offer limited flexibility to adapt to unforeseen or changing conditions. This can lead to sub-optimization if the actual conditions do not match the predicted ones.

Continuous reconfiguration allows product behavior to adapt to changing conditions in real-time, enabling optimal performance even under variable or unforeseen circumstances. The user experience is improved as the product responds dynamically to user needs and preferences. Continuous reconfiguration opens opportunities for ongoing innovation as the product can be continuously improved and optimized based on real-time data and feedback. However, the disadvantages include complexity, data protection and security, and resource requirements [39]. Implementing continuous reconfiguration requires complex algorithms and systems for real-time data processing and customization, which can make the development and maintenance of the product more complicated. It also raises privacy and security concerns, especially when personal or sensitive information is involved. Real-time data processing can also be expected to increase operating costs, energy and computing power.

Overall, both a priori and continuous reconfiguration offer different opportunities to optimize the performance and user experience of smart products. Still, they also come with various challenges that must be carefully considered.

4.2 Engineering Domain Focus

Various disciplines are essential for the reconfiguration of smart products. These can be divided into the development phase and the utilization phase. In the development phase, all disciplines that contribute to the smart product creation are usually involved. This means that the smart product's adaptability must be considered in electrical/electronic and information technology as well as mechanical engineering. Depending on the reconfiguration, these disciplines are involved to varying degrees. The more interdisciplinary the development of reconfiguration options is, the more complex and cost-intensive it becomes [40]. Conversely, reconfiguration options that only require a change or adaptation of the mechanics, for example, can be realized much more easily, quickly and cost-effectively.

4.3 Need-Oriented Triggers for Reconfiguration Options

As mentioned in the description of reconfiguration, the drivers of a reconfiguration can be different. On the one hand, as already described in the VUCA world, external circumstances can change user behavior, user requirements and other environmental conditions. Changing conditions include technological innovations that require rapid adaptation to prevent functional or qualitative obsolescence [41]. New business areas are also possible by seamlessly integrating existing or extended functions into new areas. New functions can be validated and optimized with smart products already on the market. On the user side, new requirements, e.g. for sustainability, or a change or adaptation in use or intensification, which is possible through data analysis of smart products, can be implemented quickly through reconfiguration to counteract obsolescence [42]. In the context of sustainability, smart products can be adapted to extended CE strategies, such as longevity. Technical triggers initiated by the product include faults and malfunctions that can be eliminated through reconfiguration, as well as adapting, improving and optimizing the performance of a function or product.

4.4 Barriers to Introducing Reconfiguration Options

Various barriers to reconfiguration hinder successful implementation or rule out reconfiguration options as early as during the development stage. The information technological foundations for future reconfiguration (including a coherent digital twin and its connection to digital product models) must be considered at the beginning of the development phase. Neglecting this can lead to challenges when accessing the data needed for reconfiguration, such as variant models or field data from the product’s utilization phase. Developing reconfiguration options requires a deep understanding of the product architecture, including hardware, software and interfaces. The complexity of the product architecture can make the development and implementation of reconfiguration options more difficult. Data access and availability also play a crucial role in developing reconfiguration options. However, access to relevant data sources can be challenging, especially if data is proprietary or comes from third-party providers. Integrating reconfiguration options into existing systems or products can be complex and requires careful planning and coordination. Interoperability with other systems and compliance with standards can present additional challenges. User acceptance of proposed reconfiguration options can be challenging, especially if they involve changes to the user experience or workflows. Furthermore, developing reconfiguration options requires time, money and expertise. To overcome barriers, it is essential to develop a comprehensive plan and strategy for the development of reconfiguration options that take into account the above challenges and include appropriate measures to overcome them. This may require collaboration between disciplines, stakeholders and partners to ensure successful development and implementation.

4.5 Ability to Model-Based Mapping and Tracking of New/Extended Product Reconfiguration

Smart products are usually developed based on models [6]. This makes it much easier to trace individual partial models or functions at a later date. Clear and comprehensive modeling of the product architecture, including all components, interfaces and dependencies, is essential. This includes documentation of the current configuration and potential reconfiguration options. A robust tracking system makes it possible to track changes to the product configuration, including new functions, components or interfaces. Using a version control system is essential to track changes to the product models and ensure that different versions of the product configuration are appropriately documented and managed. Automating modeling, mapping and tracking processes can improve efficiency and reduce human error [43]. This includes the use of tools and software to automate repetitive tasks. The capability for model-based mapping and tracking should integrate seamlessly with other development and operational systems to ensure a smooth exchange of information. The model-based reconfiguration tracking system should be flexible and adaptable to support different types of products and reconfigurations, regardless of their complexity or scope. Getting real-time feedback on the status and impact of reconfigurations is essential. This makes it possible to react quickly to problems and make decisions based on up-to-date information. By taking these aspects into account, the ability to model-based mapping and tracking of new and extended product reconfigurations can help to improve efficiency, transparency and control over the reconfiguration process and thus increase the quality and reliability of intelligent products.

4.6 Ability to Assess the Sustainability Contribution of the Reconfiguration Options

Various dimensions must be considered to evaluate reconfiguration options in the context of sustainability. On the one hand, the three sustainability dimensions of ecology, economy and social issues must be integrated. On the other hand, feasibility and implementation must be considered from a technical and economic perspective [44]. Reconfiguration can lead to changes in product components that have a different environmental impact than initially assumed. It is therefore essential to assess whether reconfiguration options can contribute to the resource efficiency or service life extension, for example. Assessments must be based on a life cycle analysis that can estimate features other than material consumption, such as functions. From a CE perspective, there currently need to be suitable tools to guarantee this assessment [45] fully. Nevertheless, various indicators from other areas can be used at least in part, e.g., indicators for longevity of a product [32].

4.7 Ability to Assess the Conflict of Objectives with Traditional Product Development Objectives

When developing smart products to make products reconfigurable, various conflicts of interest can arise with traditional product development. Traditional product development often places great value on the stability and reliability of a product. However, introducing reconfiguration options can increase complexity and compromise the integrity of the product. There is therefore a trade-off between the need to provide a stable product and the flexibility to reconfigure the product as required. However, by striving for continuity and consistency in terms of design, functions and processes, existing and traditional approaches take time and effort to overcome the complex integration required by smart products. However, introducing new reconfiguration options requires innovation and change, which can potentially lead to conflicting goals, especially if users or stakeholders expect a certain degree of continuity. Users often have certain expectations of their products, including ease of use, performance and reliability. Introducing reconfiguration options may not meet these expectations or may be technically challenging, leading to trade-offs between user expectations and technical feasibility [10]. Traditional product development often strives to design and manufacture products cost-effectively while providing adequate benefits to users. However, introducing reconfiguration options can incur additional costs, whether in terms of development, implementation or maintenance, leading to trade-offs between costs and benefits. It is essential to recognize and carefully consider these trade-offs to enable a balanced and successful development of reconfigurable smart products. This requires a thorough analysis, consideration and integration of different requirements, priorities and interests of the parties involved.

4.8 Reconfiguration Option Requirements

To reconfigure a smart product in the usage phase, various key elements are required that are decisive for implementation, depending on the degree of maturity or availability. The product must be designed so that it has a modular structure and different components can be reconfigured independently of each other. This enables flexible adaptation to changing requirements and conditions

[46]. In addition, straightforward interfaces and standards for the communication and integration of different components and systems are required, as well as interoperability with other systems and products and support for standards and protocols to enable seamless integration and communication, facilitating reconfiguration and replacement of components without significant problems. The product should be able to monitor its condition and performance and provide diagnostic data continuously. This makes it possible to detect problems early and identify the need for reconfiguration. The data collection must include robust security mechanisms to prevent unauthorized access and tampering.

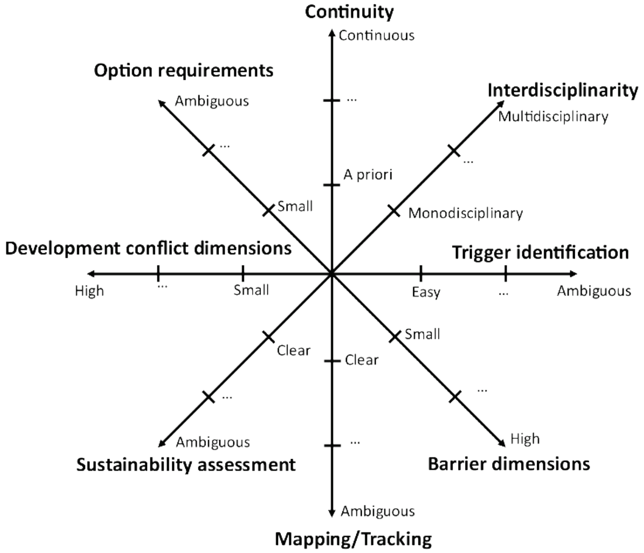

Figure 3 Indicator space for influence on Design Dimensions for reconfiguration options

This is particularly important if the product processes sensitive data or performs critical functions [47]. Additionally, data collection that can be connected to the product's user must comply with the regional data protection laws. To create a highly integrated digital twin of the product, the collected data must be connected to existing product models, especially the configuration and variant models to support reconfiguration and other service processes. Finally, the reconfiguration design dimensions presented can be brought together graphically in the dependency matrix (Fig. 3). By classifying existing products in the indicator matrix, the effort, opportunities, and risks involved in successfully introducing reconfiguration options can be identified. Depending on the degree of maturity and availability or difficulty in the dimension, an effort can be estimated.

5 IDENTIFYING DRIVERS AND GOALS USING THE EXAMPLE OF AN INDUSTRIAL USE CASE

The research consortium, which consisted of 35 partners from industry and academia, came together in 2021 and were motivated by various drivers from the VUCA world. The aim is to establish a European value creation network to manufacture products from the semiconductor industry using new technologies at substrate, device, and module levels. Enormous leaps in innovation have been made in the field of semiconductor development in recent years. The volatility in the demand for semiconductor products can change rapidly, be it due to market trends, technological developments or geopolitical events. This can lead to unpredictable fluctuations in the market, forcing companies to react flexibly to meet demand or adapt to changing market conditions. Similarly, price fluctuations are a characteristic industry feature, often due to supply and demand, competitive pressures and currency fluctuations. Uncertainty in the semiconductor industry relates primarily to technological developments and regulatory changes. Technological trends and innovations are difficult to predict and can influence investment decisions, research and development strategies and product planning. At the same time, unclear regulatory requirements and provisions lead to uncertainty about international trade agreements, data protection regulations and security standards. The complexity of the semiconductor industry is reflected in its sophisticated manufacturing processes and global supply chains. The manufacture of semiconductors requires complex production equipment and methods, which can lead to challenges in terms of quality assurance, productivity optimization and cost management. In addition, the industry's global supply chains are highly complex, making sourcing, logistics and risk management challenging. The ambiguity in the semiconductor industry is reflected in market uncertainty and technological convergence. Market uncertainties such as economic cycles, geopolitical tensions and trade conflicts influence demand, prices and investment decisions in the industry. At the same time, the convergence of different technologies leads to uncertainties about their effects and possible applications for the semiconductor industry. Overall, these challenges show how the semiconductor industry operates in a VUCA world and how companies in the industry must deal with volatile, uncertain, complex and ambiguous conditions to succeed.

The aim of meeting these challenges is to create a purely European value chain that can quickly adapt to market conditions and requirements. The product examples developed in the project aim to integrate new innovations in the field of semiconductor technology, especially about manufacturing processes, into existing products and to be able to offer new functionalities, e.g. bidirectional charging of cars makes it possible to dynamically provide electric car batteries for home use or even grid requirements [48, 49]. This functionality can be created and integrated by reconfiguring and replacing the main inverter on the vehicle side. Another goal is to increase the efficiency of the metal-oxide-semiconductor field-effect transistor (MOSFET) by introducing a modified substrate in production. However, silicon-based semiconductor materials are, in some cases, stretched to their physical limits. For this reason, on the material level, silicon carbide (SiC) has now become the focus of research, as it is not only more efficient but also more minor in design and generates less heat. By changing the material technology, goals such as more prolonged and more intensive product use can be achieved in the context of circular reconfiguration. Due to the VUCA world, the consortium is building a more consistent value chain in Europe to realize more efficient and sufficient product components, which can also be used excellently for circular reconfiguration.

6 FUTURE AREAS OF DEMAND

In summary, the two topics of reconfiguring smart products and sustainability strategies were brought together. Overlaps in scope and objectives were identified, which call for more efficiency, sufficiency, and consistency at the product level but also reveal concrete implications for developing these products. There needs to be more than existing approaches to close the research gap identified. Either there is too rigid a focus on reconfiguration in the context of goals that do not necessarily correspond to sustainability or sustainability strategies have been described too much on a material level that cannot be solved on a functional level or other overlaps with reconfiguration. The design dimensions described show current opportunities and challenges that must be solved at a specific level. Promoting the circular reconfiguration of smart products requires a holistic approach to development processes, tools, and methods. A key factor is a design for reconfigurability, which aims to design products from the outset in such a way that they can be easily disassembled, modified, and reused. This requires the integration of modular design principles and standardized interfaces to facilitate the interchangeability and upgradeability of components. In addition, development processes must consider the product's entire life cycle and factors beyond for extended, modified or second life cycles. Digital tools and technologies like the Internet of Things, big data analytics and artificial intelligence can support product reconfigurability by enabling real-time monitoring, diagnostics and customization throughout the lifecycle. Development methods should aim to maximize resource efficiency and minimize waste by integrating and implementing principles such as 9R strategies. Partnerships and collaboration between different stakeholders are crucial to address the complexity of these challenges and develop joint solutions. Overall, promoting the circular reconfiguration of smart products requires an integrative approach focusing on design innovation, life cycle thinking, digitalization, modular architectures, and CE while fostering partnerships and collaboration between different actors.

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