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Concept Paper

Managing Circular Business Model Uncertainties with Future Adaptive Design

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Abstract: Designing products that can adapt to changes over time is crucial for managing product-related business risks in circular business models. However, there is limited circular economy research on how product adaptivity can contribute to more circular products and business models, especially in the early phases of business development and design. To address this research gap, this conceptual paper builds on the adaptable design concept and incorporates ideas from research on circular business models and circular design literature. It proposes a framework we collectively term "Future Adaptive Design" to help manage product-related business risks in circular business models and investigates related design strategies for product-based companies aiming to adopt circular business models.

Keywords: circular economy; product life extension; circular business model innovation; circular product design; product obsolescence; business strategy; adaptability framework

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1. Introduction

During the emergence of mass production and consumption, the manufacturing industry turned industrial production into a mechanism for rapid acceleration of global material and resource usage by applying linear business model (LBM) logic that is considered wasteful by today's standards [1,2]. Yet, recently, calls for an alternative model—a circular economy—have been made to help address the environmental challenges arising from such LBMs and decouple resource consumption from economic activity [3,4]. In a circular economy, product life extension is widely considered one of the most promising means of slowing down resource flows and limiting the inflow of materials and energy into our economic system [5,6]. Moreover, product life extension is expected to provide firms with economic opportunities; by adopting circular business models (CBMs), firms may be able to preserve much of the economic value added to products during their production and reduce the environmental burdens associated with these products [7,8]. Thus, longer product lifetimes are considered central to the value creation logic in CBMs [9,10].

Recent CBM research has focused on developing business model typologies for how companies can create, deliver, and capture value through product life extension [11–13]. In addition, several studies have addressed challenges related to the adoption of CBMs built around product life extension [14,15]. One specific challenge is that products can fail to retain their perceived economic value over their intended lifetime [8]. This happens when products become obsolete, i.e., when users no longer perceive them as useful and/or meaningful [13,16]. When a product becomes obsolete before reaching the manufacturer's intended lifetime, it is referred to as premature obsolescence [17]. Premature obsolescence is an ever-present threat to CBMs based on product life extension [8,17]. Companies may be willing to invest in additional upfront costs (i.e., design and manufacturing) to create more durable products that reduce future costs (i.e., manufacturing and maintenance), but risk being unable to recover these investments if premature obsolescence occurs due to future uncertainties.

Future uncertainties can be defined as hard-to-predict changes in product contexts (e.g., stylistic trends, technological compatibility, legal conditions) occurring over the (planned) duration of a product's lifetime and leading to a foreshortening of a product's intended life [8]. One approach to help avert the onset of premature obsolescence is designing products that can adapt to future uncertainties [18]. Hence, it is argued that finding ways to minimize the risk of premature obsolescence by creating adaptable products could support CBM adoption. However, and up until now, a cohesive set of principles to support designers and business professionals in the design of future adaptable products for CBMs, which we refer to as "Future Adaptive Design", is lacking.

Adaptable design research [19,20] provides a useful starting point in helping to develop and establish such guidelines. Yet, to date, there appears to be little effort focused on combining adaptable design with circular economy research. This could be in part because traditional adaptable design approaches present a high threshold for usage during CBM innovation processes. Most existing CBM innovation tools are qualitative in nature and focused on generating initial concepts [21], whereas adaptable design methods are the opposite: quantitative and detailed-oriented [22,23]. Thus, the technical and quantitative approaches required in adaptable design may be prohibitively challenging for use in CBM development. Therefore, this conceptual paper addresses the following research question:

For companies wanting to adopt circular business models, what design strategies could help products adapt to future uncertainties, thus reducing the risk of premature product obsolescence?

The paper proceeds as follows: Section 2 presents an overview of our approach. Sections 3 and 4 summarize existing literature from within design engineering and circular economy research. Section 5 details how Future Adaptive Design could be operationalized for CBMs by introducing a conceptual framework of strategies oriented towards product design and business development. Section 6 reflects on limitations, outlines future research, and draws conclusions for designers, business developers, and researchers.

2. Method

This research was initiated in response to Linder & Williander's [8] identification of the need to reduce financial risks related to premature product obsolescence in CBMs. This paper first provides a background on adaptable design and related strategies from the design engineering field (Section 3). Afterwards, literature on CBMs is presented in two parts. First, a background on CBMs that extend product lifetimes is provided and future uncertainties associated with such CBMs are identified (Section 4.1). Next, circular product design strategies in literature are presented and evaluated for their ability to address future uncertainties (Section 4.2). Based on the identified gaps, a conceptual framework for Future Adaptive Design is presented. This conceptual framework was developed following principles and steps established for the process of building conceptual frameworks as described by Jabareen [24]. Research began with a mapping exercise in which known design strategies were compiled from prior literature reviews on adaptable design [19], design for X [25], and circular design [5,26]. These strategies were then analyzed for their ability to mitigate the risk of premature product obsolescence. Identified strategies were synthesized into a framework using an abductive reasoning approach in parallel with an iterative process of systematically combining, i.e., "going back and forth" [27] (p. 555)between the literature findings and the empirical observations of applied design strategies, as detailed in Sections 5.2 and 5.3 of Nyström [28].

3. Adaptable Design

Adaptable design is an established concept identifiable in the design engineering literature that initially focused on managing complexity from increased demand for product customization in mass production [29]. Adaptable design is described as a "design for X" paradigm by Hashemian [30]. Design for X (DFX) is an umbrella term that covers many design philosophies, practices, and methodologies with the aim to help draw designers' attention to specific product characteristics (i.e., the "X") [31]. Benabdellah et al. [25] categorize existing DFX methods into five categories: design for service; design for supply chain; design for quality; design for safety; and design for manufacture and assembly. Here, adaptable design falls under the latter category due to its initial application in production.

Two main approaches to adaptable design are identifiable in the literature: design adaptability and product adaptability [19]. Design adaptability is a design strategy for production. It focuses on creating designs (i.e., blueprints or CAD models) that are easily adjustable, thus increasing production efficiency [32]. The focus of product adaptability, on the other hand, is on the usage phase [20]. Designing for product adaptability equips products with the ability to change, alter, or modify capabilities and functions after their production. This allows products to respond to changing user needs, customer requirements, or other external factors [33].

Considering the importance of prolonged product usage in circular business models that extend product lifetimes, this paper focuses on product adaptability. Product adaptability design methods consider several elements: flexibility, upgradability, and modularity [19]. Uckun et al. [33] also argue for the inclusion of reliability and robustness. It is important to note, however, that robustness and reliability alone do not result in an adaptable product. Even though robustness and reliability generally contribute to product longevity, it is the product architecture that allows for or prevents adaptability. Based on Gu et al. [19], the three main product adaptability design methods are defined as follows:

- flexibility: the ability of a product to perform a different function without significant alteration;
- upgradability: the ability to apply changes to a product to achieve better performance and meet new needs;
- modularity: developing a product to have a segregated architecture that allows parts and sub-components to easily detach.

Product adaptability can be either specific or general [19]. Specific adaptability is limited to adaptions for (future) changes that are predictable. General adaptability, on the other hand, provides greater future change potential, enabling products to adapt to needs and requirements unknown at the time of design. Modularity that is achieved through a segregated product architecture is often considered key to general adaptability as it enables parts or groups of parts (modules) to be swapped or replaced, without affecting the rest of the product [31,34]. Other techniques to execute modularity include clustering—where like parts are grouped with other like parts—and platform design—where sub-components share a common base platform [35]. However, while many authors view modularity as a core part of adaptable product design, modularity is not only used for achieving product adaptability. Often modularization is used in cost-efficient production, enabling many attributes/configurations on one product platform [36]. This type of modularity does not automatically enhance the adaptability of products during their use phase. For example, the order of module assembly may not be optimized for replacement or modules may be assembled through techniques such as welding and gluing, leading to more time-consuming and costly upgrades.

Gu et al. [19] argue that adaptable design brings economic benefits for both companies and customers. Producers may be able to better address different customer needs through customization, while product owners (either customers or companies) can save costs if increased functionality through adaptable design allows them to avoid buying or making new products. In addition, environmental benefits can be achieved if new product production is avoided by replacing only a few new modules or components in already existing products. However, undertaking adaptable design also entails business risks. It may increase costs for companies because of additional product development processes [37] or increase the use of expensive materials and production processes. Product designs must also be assessed and modeled quantitatively by engineers [19], and even after adaptable design is adopted and executed, it can be challenging to determine the actual financial benefits [38]. Uckun et al. [33] suggest companies take a calculated risk when designing for adaptability, working towards an ideal long-term scenario where future income earned by being able to adapt the product and reduce future costs (or supply risks) might turn out to be lower than the initial design and manufacturing investment.

4. Approaches to Managing Future Uncertainties in CBMs

4.1. CBMs for Product Life Extension and Their Inherent Future Uncertainties

Linder & Williander [8] define a circular business model as: "a business model in which the conceptual logic for value creation is based on utilizing the economic value retained in products after use in the production of new offerings." Thus, an essential factor in the business logic of CBMs is the ability to retain control over physical products and their embedded resources [13], as this enables companies to repeatedly and reliably capture as much value as possible from extending product lifetimes. Ideally, this product value and integrity should be preserved through a sequence of systematic interventions (e.g., reuse, repair, remanufacturing, and material recycling) that is ordered in accordance with Stahel's Inertia Principle [6]. However, companies face numerous challenges with CBMs because they are a significant departure from the LBM approach.

The traditional LBM approach emphasizes the manufacture and sale of new products rather than extending the life of existing products. LBMs focus primarily on capturing monetary value from a unidirectional "take, make, use, and lose" flow of physical products made mostly from non-renewable, virgin resources in an ongoing series of one-off, transfer-of-ownership-rights transactions [39]. Profits in such LBMs arise from margins between sales price and cost for developing, producing, and selling products, multiplied by the total product volume sold [40]. In the 1920s, General Motors demonstrated one of the earliest large-scale examples of the artificially accelerated LBM approach by introducing new product models every year, a model soon emulated by other companies because it was a powerful tool for boosting product sales [41]. Today, these types of sales cycles have become even shorter in many industries, with the fashion industry offering more styles at lower prices in a shorter time period; some development and sales cycles are as short as two weeks [42].

Short product cycles may be detrimental to the environment in terms of resource consumption, but they offer companies reduced risk regarding inherent future uncertainties. Future uncertainties in CBMs can be characterized by several drivers of product obsolescence (Table 1). As noted by Burns [16], obsolescence may not only be caused by a product's lack of physical durability, but also by changes in legislation or perception including consumer behavior and preference [43,44]. In other words, products may still physically work and become prematurely obsolete, nonetheless. Previous studies confirm that product durability is often not the main reason for discarding products [45–47]. Instead, it is other factors that trigger a product to become obsolete, such as product aesthetics and changing user preferences. In these cases, even though the product might still be able to fulfill the function it was originally designed for or could do so again with minor repairs, it is still perceived as undesirable by the user [43].

Table 1. Inherent future uncertainties related to circular business models for product life extension (based on Burns [16]).

Type of Future Uncertainty	Description	How Does This Impact Circular Business Models (CBMs)?
Aesthetic obsolescence	Discarding products due to product appearance; caused by changing tastes, e.g., fashion changes, or product states, e.g., scratches and blemishes	CBMs should consider a product's aesthetics over its entire lifecycle
Technical obsolescence	Discarding products due to technical performance; caused by mechanical failure (e.g., due to wear or accidents) or the introduction of technological innovations that cause existing products to become perceived as inferior and lower performing	Products in CBMs should be able to be repaired and/or upgrade to and be compatible with new technologies
Social obsolescence	Discarding products because of changing societal trends or legislation, e.g., existing products are unable to comply with new certification rules or emissions legislation	Products in CBMs should be able to adapt or adjust to changing social trends or legislation
Functional obsolescence	Discarding products due to a mismatch between product and user needs; caused by a product's inability to meet changing user needs, e.g., need for increased space	Products in CBMs should address user's changing functional requirements
Economic obsolescence	Discarding products due to the costs of a product in use; users may discard products prematurely if cost of ownership, e.g., maintenance or repair, increases and/or lower cost product alternatives are available	CBMs should consider a product's costs over its entire lifecycle

If we consider products in CBMs from a temporal perspective, possibilities to avert premature product obsolescence not only occur during the product's design phase but also throughout the product's lifecycle. Here, Rose [48] distinguishes between two approaches: preventative and curative actions. Building on this work, two fundamental approaches to addressing future uncertainties in products are identified in this paper:

1. Preventive actions: occur in the product's design phase (i.e., before production and use); aim to improve the product's ability to avoid premature obsolescence and stay relevant for longer through better product design; help prevent premature product obsolescence by designing a product that has capacity to be expanded or modified beyond its original specifications.
2. Curative actions: occur in the product's use phase; associated with the promotion of processes and technology approaches that can be applied to products throughout their lifetimes; help avoid premature product obsolescence by continuing to support products after the design phase.

4.2. *Circular Product Design Approaches for Long-Lasting Products*

Circular design literature emphasizes the design of technically long-lasting products through robustness and durability [49]—even though most products become obsolete for reasons beyond product durability, as described in Section 4.1. In a recent systematic literature review of circular design and DFX literature, Sassanelli et al. [26] identify several circular design strategies aimed at product life extension, including design for multiple lifecycles, design for maintenance, and design for reliability. Interestingly, they also conclude that most existing circular design frameworks are theoretical and lack validation in practice.

Terms such as "product adaptability" have been used previously within circular economy design literature. Authors such as Bocken et al. [49] and Bovea and Perez-Belis [50] have encouraged product adaptability, with Bocken et al. [49] p. 311, for example, defining this as the process of "designing products to allow for future expansion and modification." However, one shortcoming of these works is they do not offer guidelines or methods for how to achieve and apply such strategies in practice. An early contribution to circular design research by van den Berg and Bakker [51] highlights the importance of designing "future-proof" products for a circular economy by making products "last long" (i.e., design for performance, reliability, and durability). The authors also point out the importance of making product "use long" (i.e., design for upgradability, adaptability, timeless design, road-mapping, and anticipating legislation). However, again, one shortcoming of this research is that the means for implementing these strategies during the design process are not clear.

Den Hollander [13] provides a more recent contribution by arguing that achieving long product lifetimes requires preserving the perceived (i.e., subjective) value of a product over time. He suggests this can be achieved by designing the tangible product in conjunction with the intangible business model context, a roadmap for planned interventions, and value propositions for the total lifetime of a product; thus, the product and its business model contexts are aligned ahead of time for the product's entire planned lifetime. His approach, however, does not explicitly account for unexpected changes in context over the preplanned lifetime of a product. This is also true for the three main design directions den Hollander et al. [5] identify for managing product obsolescence in circular business models: resisting obsolescence, postponing obsolescence, and reversing obsolescence. Each of these three directions offers several design strategies that can be used to encourage product longevity (see Table 2). Yet, the strategies give products limited ability to adapt to future changes, especially those unknown at the time of design.

Table 2. Overview of main circular design approaches (based on den Hollander et al. [5]).

Resisting product obsolescence	Design for Physical Durability
	Design for Emotional Durability
Postponing product obsolescence	Design for Maintenance
	Design for Upgrading
Reversing product obsolescence	Design for Recontextualizing
	Design for Repair
	Design for Refurbishment
	Design for Remanufacture

Managing business model innovation and product design is a complex process, arising from a multitude of actors often working in parallel and with different world views and objectives [25]. Existing research, e.g., [13,49] stresses simultaneous co-creation and alignment between business model development and product design when creating CBMs. This is because long product life spans are conceptually at odds with the traditional LBM logic. Design efforts aimed towards transitioning an existing LBM towards longer product life are likely to fail unless the fundamental business logic is changed along with the product. At the same time, as noted in Section 4.1, trying to only implement a CBM based on product life extension—without considering designing for future uncertainties—leaves companies at risk for premature product obsolescence. However, research on how exactly to align the design of products and business models for a circular economy is still in its infancy [52]. Furthermore, existing circular design strategies do not also explicitly consider to what extent the product, in combination with the business model, should be able to adapt to unexpected changes in context.

This paper therefore contributes to research on circular economy and sustainable consumption and production by providing a framework for how product design and business model development could be combined to address premature product obsolescence in

CBMs. The next section brings together literature from the fields of circular design and circular business models (Section 4) with that from the domain of adaptable design (Section 3) to develop an initial terminology and framework of strategies for Future Adaptive Design. Several design strategies are not included because they are considered outside the scope of Future Adaptive Design. This includes design for long life through physical durability because although this strategy can certainly help increase a product's potential for avoiding obsolescence, its primary aim is not to help create products that can easily be adapted or modified to unforeseen changes in future context. As such, we view this as a strategy to be used *alongside* Future Adaptive Design rather than as a part of it. Additionally, strategies such as design for resource/energy efficiency were excluded because of their lack of primary focus on product life extension. Strategies like design for quality and safety are certainly a concern in product design, but we view them as something to be considered next to Future Adaptive Design. Finally, we suggest that emotional durability could be one outcome of applying Future Adaptive Design—rather than an integral part of the framework.

The grouping of the initial strategies presented in this article is intended to help multi-disciplinary teams in the early stages of developing CBMs for product life extension. This process invariably requires involvement by not just designers but also business developers. However, these two areas traditionally have different approaches that may result in tensions about what results to achieve and how work should be done [53,54]. For example, while business model developers may focus on identifying product volumes and deciding unit pricing, designers may be fixated on product forms and desired product experiences. Therefore, an additional requirement considered when crafting our Future Adaptive Design approach was that it should be useable by both groups.

5. Towards Future Adaptive Design for Circular Business Models

Building on the two approaches for improving product lifecycles presented in Section 4.1, Table 3 summarizes the design strategies for Future Adaptive Design identified in this paper. Rather than view products as something produced at a specific time with set conditions, Future Adaptive Design views circular business models and products as "time fluid", i.e., being able to adjust and adapt over time to forces that have traditionally been exogenous to CBM innovation. Thus, Future Adaptive Design aims to assist companies in designing their products with sufficient potential to be adjusted and changed according to exogenous conditions unknown at the time of design and production, thus helping to reduce business risks in CBMs.

Table 3. Overview of the Future Adaptive Design strategies identified in this paper.

Strategies for Preventive Action	Strategies for Curative Action
• Multilayered modularity and interoperability • Lifecycle service planning	• Continuous service innovation • Cascading customer usage

5.1. Strategies for Preventive Actions

In this section, we introduce and describe design strategies related to preventive actions for Future Adaptive Design.

5.1.1. Multilayered Modularity and Interoperability

"Multilayered Modularity and Interoperability" is the first Future Adaptive Design strategy proposed in this paper. The goal of this strategy is to reduce future uncertainties and help extend product lifetimes by designing products in ways that allow future product interventions and updates in response to changes in context unknown at time of design. Multilayered Modularity and Interoperability draws on modular design approaches common in software development and graphical user interface design that enable upgradeability and adjustments of software systems [55] and from building design techniques that allow for physical changes [56]. In addition, design guidelines from adaptability [26] as well as repairability and serviceability [57] provide a foundation to address this challenge as they suggest that separating elements of a product architecture can facilitate more controlled outcomes.

One key aspect of Multilayered Modularity and Interoperability is developing a layer-based product architecture [55,58] that enables a product's components to be interchanged and updated as independently as possible. If layer-based product architecture is applied, changes can be made to one layer, without affecting the other layers. This helps combat obsolescence and assist in product value being more easily maintained over time, as various updates to a product can be done layer by layer. Interoperability, or the ability for these layers to remain compatible with each other [59], is a prerequisite to these layers working together because premature product obsolescence will occur if current and future product modules have conflicts and cannot work together. Therefore, standardization and compatibility [26,49,60] also play an important role in supporting Multilayered Modularity and Interoperability by helping to achieve product interoperability.

Examples of Multilayered Modularity and Interoperability can be found in existing products. To enable repair as well as the easy exchange of exterior design components, race cars are often designed with a tube frame, onto which a fiberglass shell is mounted, thus separating the function and shapes of the body exterior from the function and shape of the crash safety structure. This approach allows for lower cost of production tools and easier assembly, disassembly, repairs, and upgrades. In the Telecom industry, smartphone users with the Fairphone model 3 can upgrade to the 3+ model using an upgrade kit. This is made possible through a product architecture that allows for camera and speaker modules to be easily replaced and prevents users from having to buy an entirely new phone to achieve higher performance.

5.1.2. Lifecycle Service Planning

"Lifecycle Service Planning" is the second Future Adaptive Design strategy defined in this paper. The goal of this strategy is to improve the product's ability to avoid premature obsolescence and stay relevant by planning for interventions that maximize the product's lifetime. Lifecycle Service Planning draws on design strategies such as design for maintenance [26] and road-mapping [13,51]. Here, scenario planning [61] can provide an approach to foresee potential and likely future uncertainties. The maintenance discipline "reliability-centered maintenance" focuses in part on foreseeing possible equipment failures and planning maintenance interventions [62]. Similarly, procurement and management disciplines "total cost of ownership" and "life cycle costing" aim at estimating costs that occur beyond the initial acquiring of the product [63]. Product lifecycle management is also another approach for managing a company's products over their entire lifecycle [64].

While multilayer modularity and interoperability focuses on designing a product to allow for interventions, Lifecycle Service Planning focuses on identifying and planning for interventions. In Lifecycle Service Planning, scenarios are created for the replacement of specific product components due to anticipated future uncertainties. For example, necessary component replacement can arise due to anticipated technical failure. However, changing aesthetic trends, new standards, or upcoming regulations are much harder to anticipate.

Like with reliability-centered maintenance, scenarios created through Lifecycle Service Planning could help consider what interventions to a product might occur or need to be able to be accommodated over its lifetime. For instance, the need for consumables, maintenance, repair, refurbishment, and other upgrade interventions can be identified by considering when various components will need to be exchanged due to obsolescence. Like with life cycle costing, the derived scenarios could also provide a basis to create overall cost calculations for the number and type of expected interventions, time requirements, and spare components needed. In this way, Lifecycle Service Planning can also be used to help identify financial risks associated with the product and its business model. For example, cost estimates could be assigned to each anticipated component replacement, shedding light on costly product upgrades. Additionally, a timeline of interventions can facilitate the process of determining the right specifications for product durability, choices of technical standards, and choices of technology in the design phase, leading to a more obsolescence resistant product.

Lifecycle Service Planning can be used to address trade-offs in the lifecycle of a product and make informed decisions about which components to choose. One example of such trade-off is illustrated in personal computers where manufacturers must decide between using two types of data storage technologies: hard-disk drives with rotating parts or solid-state drives. While solid-state drives are more expensive upfront, they offer better storage, transfer performance, and resistance to vibrations. Whereas prolonging the lifetime of a hard-disk drive computer may require replacing its drive sometime in its lifecycle, such a replacement may not be necessary if a solid-state drive is initially chosen, therefore resulting in overall lower lifecycle costs.

5.2. Strategies for Curative Actions

In this section, we describe the strategies considered relevant to curative actions for Future Adaptive Design. These strategies pertain to interventions that can be applied to products after production, i.e., during the use phase of a product.

5.2.1. Continuous Service Innovation

"Continuous Service Innovation" is the third Future Adaptive Design strategy proposed in this paper. It builds from design strategies such as design for flexibility [19] and design for service [25] and advocates the use of service offerings to address obsolescence and keep products relevant in light of unexpected changes in context. Service dominant logic has previously been proposed as a way to enhance or even replace physical products [65,66]. For example, services can be added or modified to maintain an acceptable level of user experience. Continuous Service Innovation therefore focuses on providing evolving hardware, software, or service updates to keep products relevant to users in an ever-changing context. In this way, Continuous Service Innovation works to address the concern that unexpected changes in user needs over time will make a product prematurely obsolete [43]. If businesses can develop supplementary services, new touchpoints, hardware, and/or software that satisfy changing customer wants and behaviors while keeping the same products in use, firms can reduce the risk of premature product obsolescence.

In contrast with multilayer modularity and interoperability which focuses on designing a product to allow for interventions, Continuous Service Innovation identifies which tangible (physical product) and intangible (service) interventions could be added throughout the product's lifecycle to prolong its use. Thus, in practice, Continuous Service Innovation could be deployed by monitoring current product usage or consumer behavior over the product lifecycle. This would enable companies to identify changing customer needs and new services or hardware that could be created to support product life extension. Here, digital technologies are expected to play an important role in Continuous Service Innovation by providing follow-up services [67,68] or software upgrades [69,70] to product users. Digital technologies can also be used to help inform Continuous Service Innovation and create new service content designed to address changing user needs. For example, tracking software that gathers user data and knowledge about product health can be used to inform predictive maintenance or upgrades [67,68].

Existing examples of Continuous Service Innovation include software updates which are common in vehicles and smartphones. Electric car company Tesla's v10.0 software release introduced new services such as where the car could autonomously drive to pick-up the driver and entertainment functions such as karaoke. (The release, however, did present limitations in terms of backward compatibility for older vehicle models, which highlights the importance of multilayer modularity and interoperability and complementarity between strategies, as will be discussed later in Section 6). Another example from the automotive industry is Volvo Cars "Slippery Road Alert", which was developed from existing user data. The service uses sensor data from vehicle behavior in cold weather conditions to send warnings to other drivers of the same brand within a certain range; it also provides condition information to road authorities.

Other existing examples of Continuous Service Innovation include farm tools where one specific product, such as a tractor, can be used for new agricultural applications by designing and producing new add-on tools [30]. Similarly, the cigarette lighter standard in cars has been converted to a power outlet for alternative and, in many cases, hard-to-predict uses by several accessories including portable refrigerators, speakers, and air pumps. By enabling a product to be used for many applications that could not be foreseen at the time of design, Continuous Service Innovation is thus expected to contribute to increased circularity by contributing to increased product flexibility and higher product utilization [71].

5.2.2. Cascading Customer Usage

The final Future Adaptive Design strategy proposed in this paper is "Cascading Customer Usage". Drawing on strategies such as design for multiple lifecycles [26] and cascaded use [52], Cascading Customer Usage enables businesses to address premature obsolescence by identifying emerging contexts that can keep products and components in use for as long, and with as high utilization and value, as possible. Cascading products, components, and materials from one use to another is central to the circular economy and viewed as an important way to recirculate resources and minimize the input of virgin raw materials in an economy [72,73]. Cascading is similar to the existing concepts of (1) "recontextualizing", defined as putting a product in a different context, pertaining to both function and user/owner [13]; (2) "repurposing", which suggests the idea of finding another place, context or application for a product in order to extend its lifetime [49]; and (3) the idea of "relinking", which refers to the reclamation or recycling of resource quality from a lower level to a higher level or to another substance cycle [74].

In contrast to Continuous Service Innovation which identifies interventions that can be added to a product to prolong its useful life, Cascading Customer Usage focuses on identifying other contexts (pertaining to function as well as user/owner [13]) for the product that can enable the preservation of its perceived value and thus lifetime extension. Within CBM innovation, Nußholz [75] highlights the importance of cascading usage to ensure longer product lifetimes. In particular, she recommends identifying various types of customers and situations along the product lifecycle where a product and/or its component can have a second life (or more). This can enable the identification of new customer segments and new business opportunities. Thus, through effective cascading usage, products can deliver maximum product function and revenue through multiple uses.

One example of using Cascading Customer Usage to combat premature product obsolescence is Volvo Trucks in Gothenburg, Sweden, which converts electrical bus batteries into solar energy stores for housing. When the capacity of the bus battery is down to 80% after approximately three years of intense use in city traffic, it is taken out of service. However, it is estimated that the battery can serve another 10 years in a building due to different charge cycles and instantaneous current requirements. For example, a used electric bus battery can cut power peaks in an apartment house significantly, with a payback time of 5–7 years [76]. To further capitalize on embedded materials when component reuse and remanufacturing is not or no longer possible, the potential for recapturing value through material recycling should also be considered. One example of Cascading Customer Usage here is within tire recycling, where globally, a million tonnes of discarded scrap tires are often used as energy sources in concrete manufacturing or granulated for various landfill applications [77]. Instead, the Swedish company Scandinavian Enviro Systems uses pyrolysis as a method for material recycling. With this process, discarded tires can be broken down into their ingredients including oils, carbon black, textiles, and steel wires for use in new applications, thus yielding economic returns many times that of using tires as an energy source [78]. Table 4 summarizes the introduced Future Adaptive Design strategies and how they help address future uncertainties in products.

Table 4. Summary of Future Adaptive Design strategies and how they address future uncertainty in CBMs.

	Future Adaptive Design Strategy	What This Strategy Focuses On	How This Helps Address Premature Obsolescence	Related Design Strategies	Related References
Strategies for Preventive Actions	Multilayered Modularity and Interoperability	Designing a product architecture to support interventions that allow for updates and changes over the product's lifetime	Premature obsolescence can be postponed and reversed if components on separate layers can be exchanged and upgraded. This will be valid for resisting technical, functional, aesthetical, and social changes that risk obsolescence	Design for: Disassembly/reassembly; Compatibility; Interoperability; Modularity; Standardization; Upgradability	[19,25,26,55–60]
	Lifecycle Service Planning	Planning for when components will need interventions over a product's lifetime (and when these interventions will take place)	Defines components (and their costs) and technologies that might need to be exchanged and upgraded over in a product's lifetime, thus addressing economic and technical obsolescence	Design for: Lifecycle; Maintenance; Reliability; Road-mapping	[13,26,51,61–64]
Strategies for Curative Actions	Continuous Service Innovation	Identifying emerging changes in customer needs over a product's lifetime and what can be done to keep the product relevant to users by upgrades of new software or services	Gives customers a continuous contemporary product experience based on the existing hardware, thus reducing their need to exchange for a new product. Especially relevant for aesthetical, functional, and social obsolescence	Design for: Flexibility; Recovery; Service; Supportability	[19,25,30,72–78]
	Cascading Customer Usage	Identifying usages/applications for a product and its components to maximize utility	Provides the product owner with a possibility for a revenue stream from resale of exchanged components, remanufactured components, or recyclable materials. Addresses technical and functional obsolescence	Design for: Multiple lifecycles; Cascaded use; Reuse; Recovery	[13,22,26,52,70–73]

5.3. Conceptual Framework for Integrating Future Adaptive Design to Support Circular Business

Building on the strategies for Future Adaptive Design, this section proposes a framework for Future Adaptive Design to help facilitate the adoption of product life extension business models in the transition to a circular economy. We argue, as visualized in Figure 1, that the aforementioned Future Adaptive Design strategies are integrated, and their application governed, by a concept we call "financially grounded adaptability."

In the concept of financially grounded adaptability proposed here, product and business model adaptivity are considered option values [38]. The purpose of this approach is to explore costs and potential revenues by designing and manufacturing products with a higher, or lower level, of adaptability to unknown changes in product context, i.e., to determine the business benefits of applying more or fewer Future Adaptive Design strategies. Managerial decisions on the use of Future Adaptive Design strategies should be informed through estimates of potential economic losses resulting from the occurrence of premature product obsolescence (business risks) versus potential additional revenues gained through the application of Future Adaptive Design strategies. Echoing the adaptive design literature as discussed in Section 3, an optimum must be found between economic loss resulting from the risk of premature product obsolescence and the costs associated with enacting Future Adaptive Design. An economic analysis such as the one proposed here could be a first point of guidance to academics and practitioners trying to decide whether, and to what extent, to adopt preventive and/or curative Future Adaptive Design strategies.

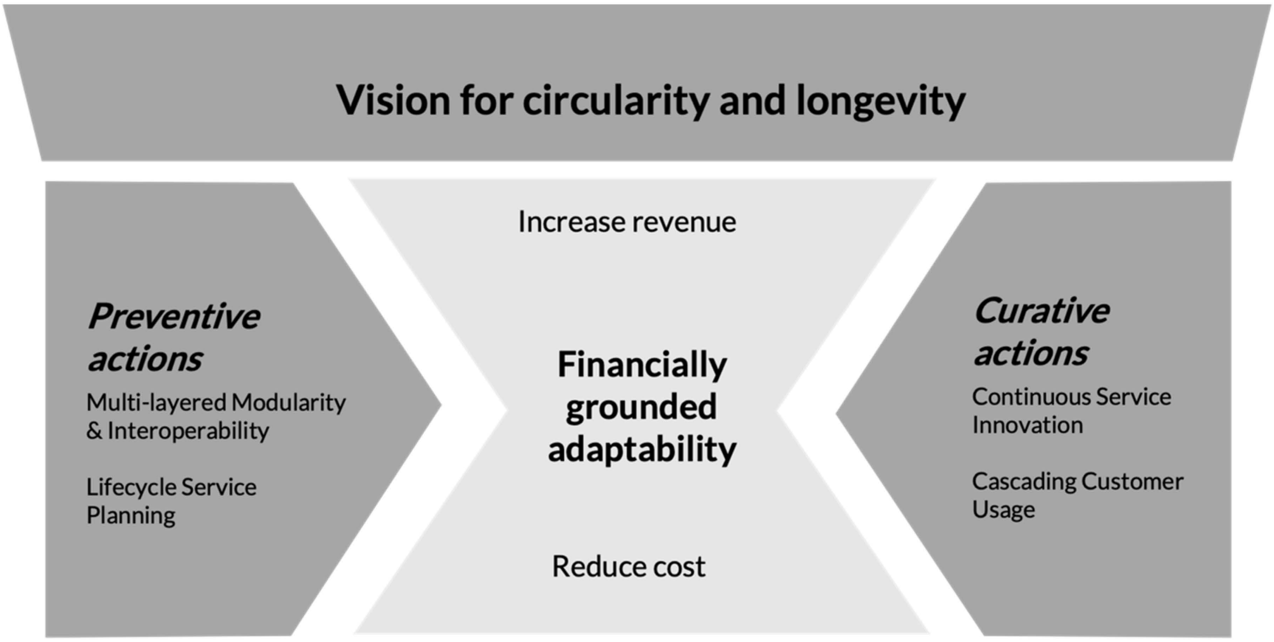

Figure 1. Future Adaptive Design strategy framework for circular business models.

In undertaking future adaptable design for CBMs, a proposed starting point is identifying potential future uncertainties and their likelihood of occurrence. Based on this analysis, some Future Adaptive Design strategies may be determined to be more relevant than others due to the types of identified potential future uncertainties. Afterwards, a next step could also be to utilize existing quantitative adaptative design approaches to further help determine the "correct" level of adaptability. For example, engineers could use methods by Fletcher et al. [22] and Li et al. [23] to determine the most suitable product architecture for interchanging and updating components as independently as possible.

As we see it, a well-described, company-specific, circular vision is a prerequisite for using the Future Adaptive Design strategies. This will enable innovators to set goals for their CBMs that are rooted in and supported by company strategy. Backcasting from this vision [79,80] could help in the selection of one or more Future Adaptive Design strategies that should be applied to help achieve these goals. Although no specific order is given here for what Future Adaptive Design strategies are best to start with in a CBM innovation process, preventive actions can only be applied prior to production. As such, multilayer modularity and interoperability and Lifecycle Service Planning must be implemented during product design before production.

As illustrated by the arrows in Figure 1, preventive and curative actions can be viewed as ways to decrease costs and increase revenue over a product's entire lifecycle. Applying the strategies in practice is expected to be an iterative process. This is because strategies complement each other and the decision to apply them is informed by their financial viability. Complementarity between strategies is further reflected upon in the next section.

6. Concluding Remarks

This paper explores how designing products that can adapt to future uncertainties could help manage product-related business risks in CBMs. Answering our initial research question, "*For companies wanting to adopt circular business models, what design strategies could help products adapt to future uncertainties, thus reducing the risk of premature product obsolescence?*" the paper introduces several strategies for Future Adaptive Design, building on the taxonomy of preventive and curative actions by Rose [48]. A framework is presented that operationalizes these strategies for developing CBMs and addressing future uncertainties. It is proposed that Future Adaptive Design is a promising option for firms to approach the uncertainty of the future by designing products with a carefully considered level of future adaptability. This includes considering the economic costs and gains involved in realizing this level of future readiness, thus providing a form of guidance to managerial decision makers, designers, and engineers.

The proposed Future Adaptive Design framework contributes to existing research on circular business models and circular design by providing a heuristic for addressing challenges encountered during CBM development through the co-design of products and CBMs. The strategies could support multidisciplinary teams by bridging the gap between business and design criteria in early circular business model innovation phases. This is because the framework reduces the complexity of traditional adaptive design research, making it more suitable for use in early CBM innovation discussions. Furthermore, the Future Adaptive Design framework provides a common language for business developers and designers to explore how profitability and product longevity can go hand-in-hand in CBMs. This could help facilitate internal company discussions related to the costs and benefits of designing products for increased longevity. Several important aspects and limitations to this study are identified for further research and development:

6.1. Strategy Complementarity

Future research should investigate how the Future Adaptive Design strategies support one another and if dependencies between strategies exist. The Future Adaptive Design strategies are intended to be used together as part of CBM innovation and to be applied in an iterative fashion. For example, designers can use Lifecycle Service Planning to help map a product's entire lifecycle, identifying which parts will need to be replaced when accommodating particular change scenarios and to evaluate whether or not this can be expected to be worthwhile. In turn, this knowledge can be used to inform multilayer modularity and interoperability and create an optimized product architecture. Moreover, viability of the business model may be at risk if the strategies are not sufficiently aligned. For example, the extent to which software update ideas generated as part of Continuous Service Innovation can be implemented will be limited by the product's existing hardware design, as well as by the need to remain interoperable with standards and technologies in the surrounding world. Due to this relationship, multilayer modularity and interoperability must be applied in ways that help enable Continuous Service Innovation. One solution could be that outdated hardware components are swapped with updated modules to assist with complementarity between product hardware and software.

6.2. Framework Testing and Assessment

One limitation of this paper is that the Future Adaptive Design framework has not been empirically assessed. Future research should test the framework with businesses aiming to develop CBMs based on product life extension. Testing is expected to reveal additional insights for both the identified Future Adaptive Design strategies and proposed framework. It is possible further testing will reveal additional strategies for both preventive and curative approaches, as our proposed list is non-exhaustive. Testing is also anticipated to provide more information about the usefulness of the framework to CBM innovation and identify obstacles to Future Adaptive Design implementation. For example, although the framework is intended to support multi-disciplinary teams, it is possible that companies encounter difficulties working with the framework or lack data required to approach financially grounded adaptability. The framework and strategies are currently being applied and tested in practice by the authors with business and product developers from manufacturing firms in the automotive, elevator, and material handling industries. However, as this research is ongoing, understanding of their effectiveness in practice is limited.

Further research may identify limits to the extent that companies can apply Future Adaptive Design in practice. Company position in the value chain may affect its ability to implement Future Adaptive Design. If companies have limited control over hardware and software specifications, applying Future Adaptive Design strategies such as multilayer modularity and interoperability or Continuous Service Innovation may be more challenging as compared to companies having complete control. For example, as a relatively small mobile phone manufacturer, Fairphone is squeezed between large subcontractors of electronics and operating systems who have greater influence on component lifetimes and compatibility between different versions of software applications. Thus, Fairphone subcontractors dictate the "death date" for the hardware, for example, if the production of a chipset model is stopped or if a newer version of Android no longer supports the previous chipset. The presented Future Adaptive Design framework does not currently provide ways to address this; however, understanding such limitations and associated risks is necessary and should be further investigated.

The study has also not investigated company interest in Future Adaptive Design approaches. There may be limits to the extent companies are willing to apply Future Adaptive Design in practice. We assume one prerequisite for Future Adaptive Design is that companies desire to adopt CBMs based on product life extension. However, not all companies may have interest in such models. This might particularly be the case in developing nations where companies have been documented to be less engaged with environmental responsibility [81]. Still, Future Adaptive Design may even be attractive to such firms if it is a way to increase market competitiveness, save costs, or increase profits. Moreover, another presumed limitation of the research is its lack of applicability to bioeconomy applications such as agricultural waste [82]. This is because most of the strategies in the literature that the current framework draws from are aimed at designing durable goods. Thus, future research could focus on the applicability and attractiveness of Future Adaptive Design, both to firms in developed and developing countries and in different industry sectors.

6.3. Environmental Considerations

Extending product lifetimes is promoted as an important avenue to reducing environmental impacts [83]; it allows spreading impacts from production over more use or function. However, extending product lifetimes does not always reduce environmental impact. Particularly with energy-consuming products, new products may be more efficient than older ones, and in these cases, product replacement could prove more environmentally beneficial than prolonging product use [10,84]. Because the Future Adaptive Design framework does not specifically account for this, business developers and designers must be sure to review the ecological impacts associated with prolonging the product life of a specific product. Future research could also aim to integrate this aspect more directly into the existing Future Adaptive Design framework. Embedding environmental aspects into this framework would also align with recent research that highlights the importance of adding environmental value to existing cultural values [85].

At the same time, however, the Future Adaptive Design strategies could likely already help address this concern. For example, multilayer modularity and interoperability can enable the upgrading of inefficient product parts to improve product efficiencies. Moreover, while the Future Adaptive Design framework presented here promotes balancing economic costs and benefits by means of financially grounded adaptability, a similar approach could be taken with ecological costs (environmental impacts). To enact environmentally grounded adaptability would merely require a different data set. For example, by using lifecycle inventories also used for lifecycle assessments, practitioners can evaluate the ecological impacts associated with adapting products for extended lifetime and avoid creating adaptive product-service offerings that result in more environmental impact than their non-adaptive counterparts [84].

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