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# Circular products: the balance between sustainability and excessive margins in design

Arindam Brahma [1,✉], Sophie I. Hallstedt [1], David C. Wynn [2] and Ola Isaksson [1]

[1] Chalmers University of Technology, Sweden, [2] University of Auckland, New Zealand

✉ brahma@chalmers.se

**Abstract**

As the world deals with climate change, it is crucial that new products are designed to be more sustainable. Product design strategies which conform to the Circular Economy principles have recently gained attention, which promote sustainability and resource efficiency. However, such strategies require careful consideration of uncertainties and the ways to mitigate them, e.g. by using margins. The pursuit of circularity can inadvertently lead to overdesign as designers strive to mitigate elevated risks, thereby making a product less sustainable. In this paper, we explore this balance.

*Keywords: sustainable design, product design, circular economy, margin, uncertainty*

## 1. Introduction

As the world deals with the effects of climate change, the adoption of sustainable practices has emerged as a paramount priority for engineers, researchers and policymakers (Wang *et al.*, 2022). In the last few decades, significant effort has been put into the search for solutions which could potentially help reduce the effects of otherwise unsustainable practices and thereby have ecologically sustainable development (Pigosso *et al.*, 2015). In product development, Design for Sustainability is a commonly used umbrella term used for design strategies and methods which focus on making the product sustainable (Byggeth and Hochschorner, 2006; Ceschin and Gaziulusoy, 2016). A subset of such methods which focus particularly on design practices which conform to the concept of circular economy (known as Design for Circular Economy or DfCE) is particularly seen to be promising (Moreno *et al.*, 2016). A product designed for a circular economy is expected to have multiple use cycles (Mestre and Cooper, 2017), for example by being easily upgradable or having components which can be re-used for fulfilling alternative secondary functions (Bocken *et al.*, 2016; Linton and Jayaraman, 2005).

On the flip side is the problem of excessive margins in a design, which is often overlooked by engineers and designers. Margins, which are defined as the difference between a design parameter’s minimum required value to ensure functionality and its actual capability (Eckert *et al.*, 2019), are often incorporated into products, either deliberately or inadvertently by design engineers (Brahma and Wynn, 2020; Eckert *et al.*, 2004). The practice primarily comes from various strategies employed for uncertainty mitigation, which is often based on intuition and experience (Brahma *et al.*, 2023). There is also a tendency to 'err on the side of caution', which at times leads to highly and unnecessarily overdesigned products (excessive margins) (Jones and Eckert, 2023). While some margins may be necessary, for instance for upgradability or to prolong a product's life, unnecessarily added margins can make a product less sustainable.

For circular product design, however, the enablement of future (partial or full) re-use of products may dictate that the products be incorporated with margins deliberately. For example, margins may be incorporated against performance degradation from wear and tear to prolong life. Margins may be incorporated in interfaces to make a product modular (Hamraz et al., 2013). The uncertainties of such re-use therefore must be studied carefully, and (only) appropriate margins allocated to achieve circularity. This paper, therefore, looks at these two concepts of circular product design and the role of margins in it. Of the three dimensions of sustainability, i.e. ecological, economic and social (Gibson, 2006), this study will have a limited focus on ecological and economic aspects. We argue that there is a fine balance between circular product design and adding excessive margins which designers must understand. Striking this balance is essential, as a product with excessive margin may result in wastage, undermining its sustainability, especially in terms of its resource efficiency, while a product with less than adequate margin may fall short of achieving high circularity, leading to similar consequences of unsustainability. In this context, designers play a crucial role in understanding and implementing the principles of circularity to ensure products align with the principles of waste reduction, resource efficiency, and environmental preservation.

**Table 1. Design for Circular Economy Strategies as described by Bocken *et al.* (2016)**

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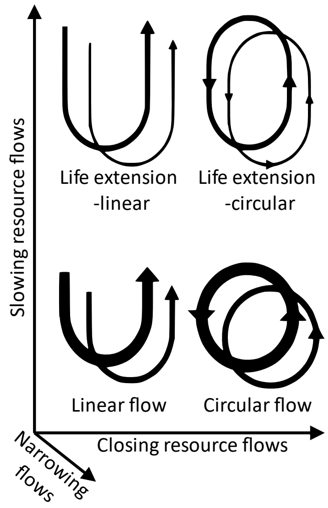
|---|---|---|
|  | Design strategies to slow loops | Designing long-life products<br>• Design for attachment and trust<br>• Design for reliability and durability<br>Design for product-life extension<br>• Design for ease of maintenance and repair<br>• Design for upgradability and adaptability<br>• Design for standardisation and compatibility<br>• Design for dis- and reassembly |
| | Design strategies to close loops | • Design for a technological cycle<br>• Design for a biological cycle<br>• Design for dis- and reassembly |
| | Design strategies to narrow flows | • Design for resource efficiency |

## 2. Background

### 2.1. Concepts of circular product design

Alternative to the traditional linear model of product economy which is often described with the phrase "take, make, dispose", Circular Economy (CE) is envisioned to have a more regenerative and restorative approach to production and consumption (Bocken *et al.*, 2016). Broadly based on principles such as reusability, repairability, recycling, ecodesign, sustainability of supply, and responsible consumption (Esposito *et al.*, 2018; Gallaud and Laperche, 2016), several descriptions of CE can be found in literature. For instance, specifically in the context of product design, den Hollander *et al.* (2017) describe CE as where, *"...the economic and environmental value of materials is preserved for as long as possible by keeping them in the economic system, either by lengthening the life of the products formed from them or by looping them back in the system to be reused."*. Based on such principles, Circular Product Design or Design for Circular Economy (DfCE) are design approaches that aim to create products with extended lifecycles (Carlsson *et al.*, 2021), reduced waste (Burke *et al.*, 2023), and increased potential for reuse and recycling (Tam *et al.*, 2019). The broadness of the topic has led to many theoretical frameworks. For instance, Potting *et al.* (2017) present the well-known 9R strategies which include Refuse, Rethink, Reduce, Re-use, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover. In another instance, keeping the resource flow view in mind, Bocken *et al.* (2016) introduce the basic strategies related to CE in terms of three types of resource cycles; slowing, closing and narrowing loops. While slowing relates to all strategies which result in the slowdown of the flow of resources such as through repair, remanufacturing or through the design of long-life products; closing refers to complete (realistically a highly efficient) recycling of resources leading to a closed loop system. The third strategy called narrowing on the other hand is aimed at reducing resource consumption and improving the efficiency of a product throughout all its lifecycle processes, for example, by better design. Based on these broad conceptual strategies, particularly slowing and closing, Bocken *et al.* (2016) suggest a host of more granular DfCE strategies which are presented in Table 1. Similar DfCE guidelines are also presented by Mestre and Cooper (2017). Besides the conceptual ideas of closing and slowing, they suggest two additional strategies which are bio-inspired and bio-based. Bio-inspired loop strategies derive primarily from the field of biomimetics whereas bio-based loops aim to increase the utilisation of natural and biological materials, which at the end of the lifecycle can be returned to the environment (Potting *et al.*, 2017).

Critics also point to some potential challenges in implementing these principles in practice. Firstly, many of the strategies could be conflicting, for example, durability vs recyclability (Kravchenko *et al.*, 2021) or situations where increasing modularity to increase upgradability can lead to increased material use (Schischke *et al.*, 2019). Researchers also allude to the conflicting public policies which have emerged as a consequence (Dalhammar Carland Milios, 2021). Further, there are economic challenges, such as the 'rebound effect' derived from economic theories (Castro *et al.*, 2022). It refers to the unintended consequences that can occur when efforts to improve resource efficiency or sustainability end up increasing resource consumption or environmental impacts instead of reducing them. As efficiencies increase, prices decrease leading to an increase in consumption, thereby nullifying the efficiency gains (Korhonen *et al.*, 2018). An analogous concept in product design would be to aim to make a product resilient, for example, making it adaptable or flexible but in turn overdesigning it by incorporating margins and features beyond what is needed (Jones and Eckert, 2023).

In addition to the framework-based and economic challenges, the literature also highlights the presence of technical issues, which can be difficult to overcome. For example, many materials cannot be recycled indefinitely due to impurities. Further, just recycling involves transportation, uses energy, produces waste, etc., which must be accounted for i.e. the challenges arising from the thermodynamic limits of a system. Georgescu-Roegen (1971) argues that the fundamental laws of entropy will never allow for a full recovery of the resources put into a system and therefore never achieve full circularity. However, counterarguments point to the infinite source of solar energy which may be harnessed. While entropy lost can never be recovered, the energy lost in the ecosystem can be substituted using solar energy (Korhonen *et al.*, 2018). Further, there is also the issue of contamination (Baxter *et al.*, 2017), processes to separate materials may either not be available or may be economically infeasible. While there may be theoretical solutions, in practice when it comes to complex socio-technical systems, especially where products are to be designed for a somewhat uncertain future, makes decision-making in design difficult. A product designer may not know what kind of functions the product (or parts of it) might need to fulfil after its 'primary lifecycle', e.g., in re-use or re-manufacturing. Or, if the intention is to make a product durable, the uncertainties associated with its use, for example, unknown-unknowns (Hastings and McManus, 2004). Designing when uncertainties are improperly quantified, can have a significant and potentially adverse effect on the circularity of a product. In the next section, we discuss the concepts related to uncertainty in product design and the ways to mitigate them in more depth.

## 2.2. Uncertainty mitigation in product design using margins

Engineering design, by its nature, involves uncertainty covering various aspects of the process (Earl *et al.*, 2005) and as highlighted by Suh (1999), is considered a fundamental element of design complexity. In the engineering design process, the sources of uncertainty may include requirements, manufacturing, operational use, and so on. Among many classifications of uncertainties, Hastings and McManus (2004) classify them into five categories. The first category involves uncertainties from lack of knowledge, which refers to the facts that are known imprecisely or are not known at all. Second are uncertainties which derive from lack of definition, which in the context of design are the aspects which are in an uncertain state for the lack of decision or specification. Third are the statistically characterised variables which relate to uncertainties which can be quantified statistically e.g. with a probability distribution. The fourth and fifth categories are known unknowns and unknown-unknowns. Known-unknowns, unlike the third category, cannot be quantified but can be identified qualitatively e.g. performance of a future technology. Whereas, unknown-unknowns, cannot be anticipated in any way such as the Covid-

19 pandemic or a natural calamity. Similar to Hastings and McManus (2004)'s classification, Earl *et al.* (2005) put the uncertainty types on two orthogonal axes. On one axis are the uncertainties based on whether they are known or unknown, whereas the other orthogonal axis represents whether the uncertainty is in description or in data.

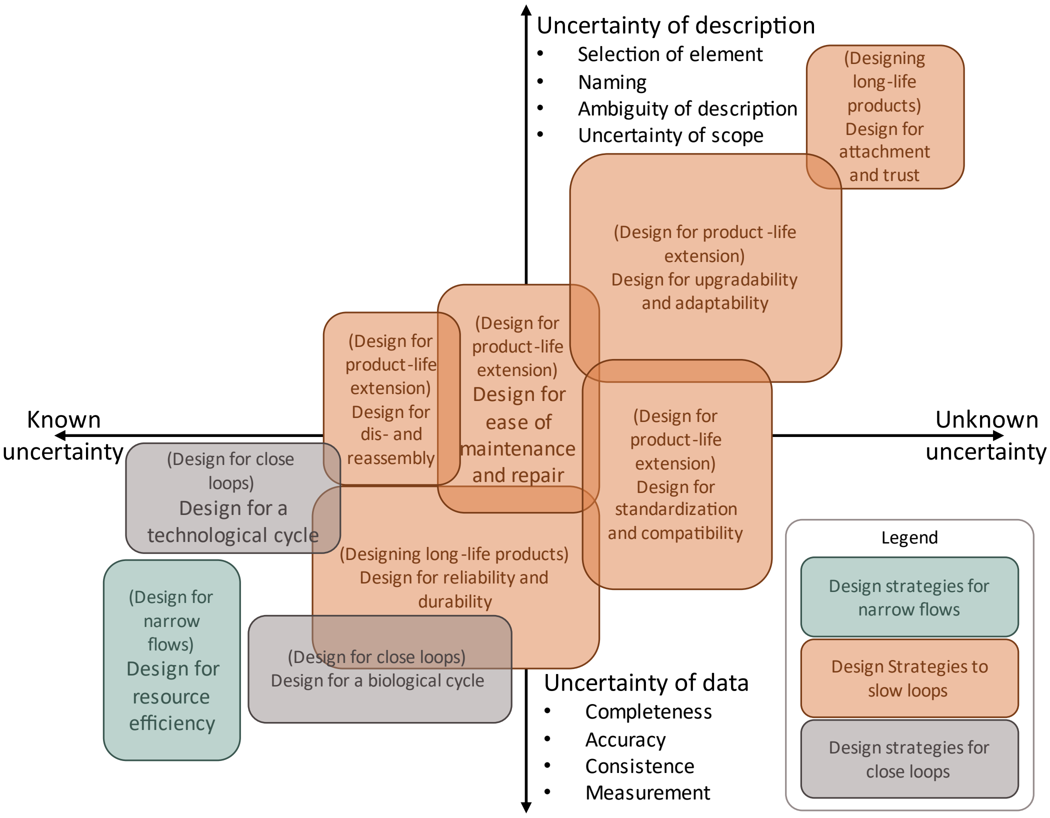


**Figure 1. Circular product design strategies as described by Bocken et al. (2016) mapped onto the uncertainty classification framework of Earl et al. (2005)**

As a mitigation strategy against such uncertainties, engineers often use margins in some form or the other which act as buffers. Safety factors are perhaps the best-known examples of margins which are targeted towards making a design safe (Möller and Hansson, 2008). Margins may be added to a design to account for future operating conditions (Levine and Hawkins, 1970), or added to prevent the propagation of changes in a design, or to ensure upgradability (Brahma and Wynn, 2020). Apart from deliberately added margins, margins may also get added unintentionally or indirectly as a byproduct of other decisions for instance stopping optimisation before all margins are removed (Eckert *et al.*, 2004) or due to the inclusion of off-the-shelf parts which have their own margins, that are often overlooked during integration analyses. These allowances are commonly undisclosed by suppliers, aiming to mitigate organizational vulnerabilities and safeguard proprietary information (Eckert *et al.*, 2020).

To achieve a complete (or even a very high degree) of circularity, it is important to understand the uncertainties which occur throughout the lifecycle(s) of a product, and by extension, the potential ways to mitigate them. It is also important that such mitigation happens in the design phase itself, as unknown future states, for example, re-use scenarios or secondary functionalities, only make the probability of failure in terms of achieving circularity, high. The lack of certainty about a system's possible behaviours and outcomes also significantly impacts requirement definition thereby also affecting circularity. While margins are one way that engineers reduce the risk associated with resolvable and unresolvable uncertainties (Eckert and Isaksson, 2017), they also have their disadvantages. Larger than necessary margins may lead to overdesign and deteriorated system performance (Brahma and Wynn, 2020). For circular design, where most strategies require approaches such as upgradability, flexibility, increased life etc., which are all achieved by adding margins, it is important that such margins are balanced with the goals of circularity.

## 3. Margins to mitigate uncertainties in circular product design

As previously mentioned, a product and its use (or a system and its operation) encounter many types of uncertainties in its lifetime, which must be taken into consideration while designing. Hastings and McManus (2004)'s framework, for example, is rooted in the principle that uncertainties give rise to risks, which are managed through specific mitigation strategies (such as by using margins), ultimately resulting in favourable outcomes. However, if seen from the other direction, if desired outcomes are known (or anticipatable like in circular design), the mitigation strategies, such as margins, must be (pre)incorporated in design, which can be done by understanding the risks. To understand the risk, one needs to understand the causal uncertainty, i.e. the factors which lead to certain outcomes. In this section, we use this understanding in the context of circular design strategies to map the desired outcomes with the associated uncertainty. As a framework for discussion, Figure 1 shows the design strategies as mentioned in Bocken *et al.* (2016), mapped onto Earl *et al.* (2005)'s uncertainty classification, previously described in Section 2.2.

### 3.1. Margins added to products to slow loops

#### *3.1.1. Margins when uncertainties are unknown*

Products which are designed with a long life in mind may encounter uncertainties which are specific to the intended design strategy used. For example, if an extension of life is to be achieved by designing the product to be upgradable and/or adaptable, the related uncertainties may manifest from the unknowns of the future. In such cases, margins may be added, for instance in the interfaces of modular products designed to a standard specification. If the products are to be made upgradable and adaptable, for example, by making them modular, interfaces may need to be designed for the demands of the highest application. For instance, if a laptop is designed to accept battery modules spanning a range of powers, its interface and other associated electronics must be designed to handle the highest-powered battery in the product portfolio. The 'low-end' variants would always end up with a significant amount of margins, which remain unused, till the user upgrades. Further, technology development cycles are often difficult to predict and the scope or extent to which the products ought to be upgradable or adaptable is often vaguely or ambiguously defined. Strategy to design for compatibility and standardisation has similar unknown uncertainties. While common standards could be created and used, they may constrain future technological development. Unlike design for upgradability and adaptability, however, the uncertainties in knowledge in this strategy predominantly originates from uncertainty of data where consistency is a must to achieve a truly standardised product. There is also some overlap between these two uncertainties, as upgradability and adaptability often require the interfaces to be somewhat standardised. If and when such a technological shift occurs such that the margins are unable to absorb the changes, products may either need to be discarded creating waste or refurbished to prolong their life. The amount of margin added to achieve circularity therefore arguably necessitates a predictive outlook on the direction (unknown uncertainties) and amplitude (uncertainty of data) of such a potential technological shift.

#### *3.1.2. Margins when uncertainties are known*

The second subtype of strategies falls on the left side of Figure 1, where uncertainties are known. The first strategy here is to design for maintainability and repairability. For established products, the uncertainties, are usually known as product designers often have a very good idea of which parts are most likely to fail or need maintenance, for which margins can be strategically allocated. Examples may include safety redundant power supplies in computers to ensure continuity in functionality in case of failure of one. Note that this however may change when the product is not yet well established, such as in the case of systems with complex interactions, i.e. uncertainties are unknown. Additionally, this does not consider unpredictable usage patterns and scenarios, which may lead to uncertainty in description of scope, against which designers may scope such factors. Similarly, environmental scenarios may produce uncertainty in data, for instance in terms of ambient temperature fluctuations beyond the testing environments of products. Similarly, the strategy to design for durability and reliability is also a well-used strategy and shares some of the characteristics with the previous strategy in terms of the quantification of uncertainties. Examples, where margins are added to increase durability, could include corrosion allowances for products used in corrosive environments or margins in the form of increased material strength to counter wear. Making a product durable may also include designing for unanticipated loading conditions, i.e. adding margins to absorb varying loads, which may also be done to make a product reliable in operation. For both maintainability/repairability and durability/reliability-led designs, uncertainties may arise from measurement errors, unknown complex interactions, or other data-related sources when reliability is quantified by design engineers. Based on the quantification, known to a certain degree of confidence, margins may be allocated appropriately to mitigate them. However, attempts to make a product infinitely durable, repairable, and maintainable, may lead to over-allocation of margin, which is counterproductive, as it will lead to wasteful over-capacity, which may never be used. Similarly, margins (e.g. a redundant system) where risk of failure is minimal, will also lead to unused and wasted capacity.

### *3.1.3. Margins against uncertainties of description*

Design for dis- and re-assembly on the other hand mostly requires known uncertainties of data to be mitigated in the design, which may arise from component compatibility, expected wear and degradation, component durability and so on. However, there could also be uncertainties in scope especially related to the extent the design must be disassemblable. Further, the trade-offs dis-assemblability may have with a product's performance and integrity. All these strategies also have certain overlaps. Ease of assembly and disassembly, for instance, go hand in hand with repairability. The uncertainties related to durability on the other hand overlap with uncertainties related to maintenance and repair, however with an inverse relationship. The higher the durability, the lower the likelihood of the need to repair. Similarly, design for dis- and reassembly may require additional features to be built into a system which may be otherwise unnecessary. Considerations to incorporate margins may include interface design and its degradation from repeated dis- and reassembly, safety issues to facilitate safe assembly operations, manufacturing tolerances and so on. Similar to the cases mentioned in the previous paragraph, margins added to make a product easy to assemble and disassemble may also lead to wasted excess capacity in the design.

The final DfCE strategy in this category is described as "Design for attachment and trust" (Bocken *et al.*, 2016). This strategy finds itself in the top right corner of Figure 1. The uncertainties related to this strategy primarily come from the subjectivity of the resulting designs. People may perceive and interpret designs differently based on their emotional variability. Further, such responses may heavily depend on context, cultural differences and so on. Not only the predictability of such uncertainties is difficult, but it is also often extremely difficult to specify the scope and requirements for products which need to be designed for attachment and trust. Such uncertainties may motivate the designer to add margins unnecessarily leading to over-design and overfeaturing of products. For example, when the designer intends to design for attachment and trust, the subjectivity associated with user perception of the product may motivate the designer to incorporate unnecessary features, also a kind of margin in design. These margins may remain unutilised if the said features are never used to their full functionality. Similar are margins added to make a product flexible. Margins may be added to gain flexibility in a product which may never materialise. An example may include many ports and interfaces on computer boards which are often unused.

## 3.2. Margins added to design to close loops

The second set of DfCE strategies is aimed at closing the loops, primarily aiming at either materials being completely recycled or materials being "compatible with biological cycles", expected to bio-degrade without causing much harm to nature. In the terminology proposed by Bocken *et al.* (2016), the first strategy is termed "Design for technological cycles" and the latter is termed "Design for biological cycles". Design for closing loops aims at the selection of material which can be completely recycled, with high efficiency and eventually fed back to the system (den Hollander *et al.*, 2017). While uncertainties relating to the recycling of materials (e.g. uncertainties relating to recycling efficiency) may be mostly known, the challenge arises from designing products which are easy to recycle. This is especially the case for multi-functional complex products such as smartphones and other electronics which are made of hundreds of thousands of parts all of which have different recyclabilities but are tightly integrated for functionality. Assuming the possibility that most, if not all material required for a design is recyclable, the designer can make the product highly non-integrative, such that parts can be taken apart easily to recycle. This will require the design to be inefficient, for example by the introduction of interfaces which are otherwise not needed, or even additional parts to create those interfaces. These are additional non-functional margins which have an indirect cost to the product's circularity. For this design strategy to be successful the extra energy, material etc. spent on creating such margins (extra interfaces) plus the energy needed for recycling must be lesser than the waste produced from a non-recyclable (or less recyclable) product. For complex products, this trade-off is not very straightforward.

Further, inaccurate loss estimates may lead to poor performance of designs where the recycled material may be reused. The overlaps with the two strategies related to slowing loops as shown in Figure 1, shows the relationship between the uncertainties. A designer must consider easy disassembly for more efficient recycling whereas, highly durable products may not need recycling as often. Finally, if a part is expected to be recycled at the end of its primary life cycle, designers may incorporate margins counter for a certain level of contamination or mixed materials, which must also be accounted for.

### 3.3. Uncertainties in design strategies to narrow flows

Narrowing flows is somewhat different from the other DfCE approaches of closing and narrowing loops. Researchers such as Bocken *et al.* (2016) argue that since narrowing is primarily aimed at resource efficiency, which does not require the design to be specifically circular. Therefore, narrowing need not be considered a separate strategy but should be seen in conjunction with other strategies stated in the previous sections. Regardless, there are uncertainties associated with which a designer must mitigate. For instance, to achieve the same levels of functionality with drastically fewer resources, the designer must accurately quantify the uncertainties associated with the alternative means. While there may be opportunities to cut processes-related inefficiencies, designers must be aware not to over-correct such that the process collapses. Well-quantified margins can help in mitigating such uncertainties. Prime examples include manufacturing tolerances, time margins in production schedules etc.

## 4. The delicate balance between DfCE and excess margins

The DfCE strategies promulgated in literature all need margins of some kind to mitigate uncertainties. In addition to the discussion in the previous section, we derive from Brahma *et al.* (2023)'s list of margins which appear at different stages of a product development cycle and map them to the commonly used DfCE strategies as shown in Figure 2. For example, if the designer intends to design for durability, margins may be added such that the wear and tear over the life of the product. While it may not be exhaustive, it gives a general indication that margins are an important issue to consider when designing products especially when design strategies are for sustainability and circularity is to be considered. Researchers state that while considerations for circular product design is motivated by the sustainability of products at their end-of-life cycles, the influencing decisions are often taken very early in its design cycle (Wang *et al.*, 2022). However, the challenge comes with knowing (or not knowing) the uncertainties and designing for them. Especially for circular product design where products may have more than one life, such uncertainties may be difficult to discern. While the known uncertainties may be mitigated by precisely allocating margins by designers, speculative uncertainties can be detrimental to the overall sustainability of the design. If the designer intends the design to be circular, they may end up designing functions and other characteristics which may be speculative thereby creating unnecessary margins in the product. Such margins may be more harmful than useful when it comes to sustainability and must be carefully judged. Lifecycle assessments therefore should include an assessment of margins, and their utility (and also necessity) when designing for a circular economy. Aiming for a high degree of circularity when uncertainties are high may only lead to excess margins in products which is counterproductive when it comes to sustainability, especially considering resource efficiency. Concepts such as "lifetime embodied energy" (Lordos *et al.*, 2023), can also be used to understand this balance. As in Equation (1), the total embodied energy of all the margins added to a product to make it circular ($E_{margin}$) and the total energy consumed in processes between lifecycles ($E_{tl}$; such as in remanufacturing, repair, recycling etc), must be lesser than the total embodied energy of the equivalent non-circular product ($E_{eol}$; including all the embodied energy wasted at end of life), for it to be a more sustainable product. Several approaches which can potentially be used to accurately quantify the margins in a design can be found in literature (Brahma *et al.*, 2023). The accurate quantification of margins and tracking them throughout the lifecycle of a product is necessary to confidently estimate whether there is a "net benefit" in adding margins to a design to make them circular.

$$\frac{E_{margin}+E_{tl}}{E_{eol}} < 1 \tag{1}$$

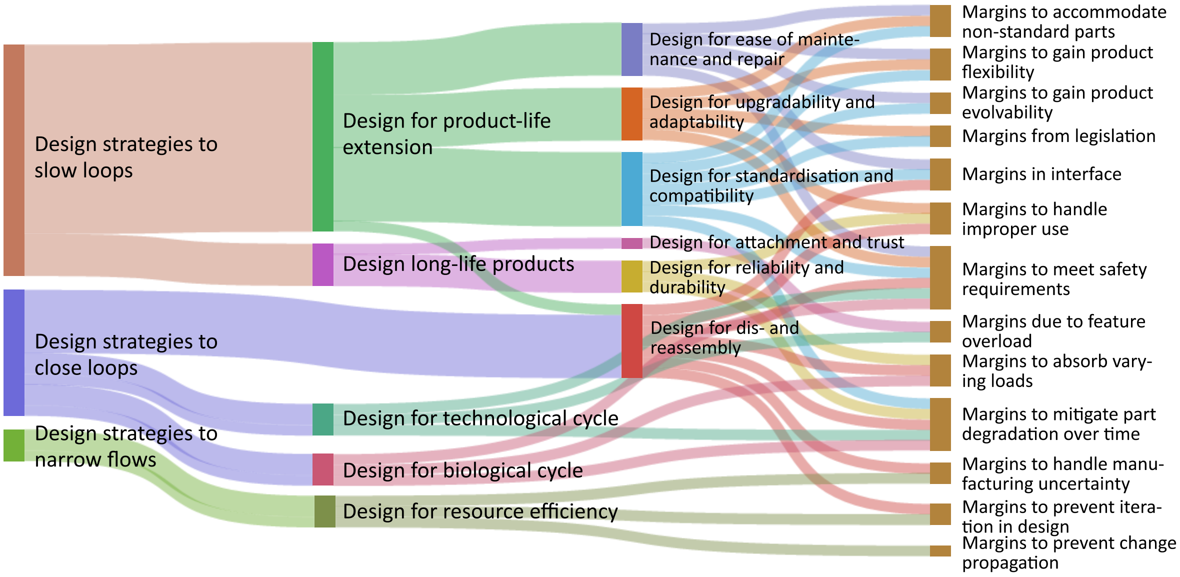


**Figure 2. Map of selected DfCE strategies and potential margins to mitigate uncertainties**

## 5. Conclusion

Creating sustainable products is a challenge which must be solved with significant urgency given the rapidly deteriorating climate conditions. Design for Circular Economy aims to create frameworks which will eventually help design engineers in designing products which are sustainable and have little to no impact on the environment. While circular product design is becoming popular in promoting sustainability and resource efficiency, there exists a nuanced challenge that requires careful consideration. The pursuit of circularity can inadvertently lead to excessive margins in a design (overdesign), as designers strive to mitigate heightened uncertainties. This potential overdesign arises from the need to accommodate uncertainties in future recycling processes, ensure compatibility with evolving technologies, enable modular replacements and so on. Therefore, achieving a balance between allocated margin and circularity is essential. Designers must critically evaluate the trade-offs between added margins and the risks of overdesign with the gains expected from a circular product. Addressing this challenge will be pivotal in realising the full potential of circular product design while avoiding unintended consequences of overdesign in terms of complexity and more importantly, environmental impact. While margin quantification methods exist and gaining popularity, their use in the context of circularity and sustainability quantification is missing from literature. Future work includes margin tracking methods to accurately measure margins in the value chain and frameworks to help designers keep the balance between the desirable and undesirable effects of margins on a product's circularity. From a broader DfCE perspective, the challenge extends beyond the concept of "sustainable products" and encompasses systemic issues such as consumer behaviour, which pose difficulties in quantification for margin analysis. For instance, the design of a product featuring reusable components, as highlighted in the paper, loses its effectiveness if individuals choose to discard their items instead of repairing or upgrading them, or if the design negatively impacts its functionality. Similarly, a product's potential for a second life holds no value if there is no demand for second-hand items. Furthermore, the overall cost of the product, factored into the margin, raises concerns about whether individuals with limited resources can manage the increased expenses linked to the design effort and initial product cost at the point of purchase, irrespective of its extended durability. These systemic issues also demand a design approach that goes beyond the product itself.

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