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Circular design, state of the art review

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Circular design, state of the art review
Technical design point of view

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Summary

The current take-make-dispose economy is based on the rapid procurement and satisfaction of needs, and does not emphasise on sustainability. The production of goods requires a large number of primary resources (e.g. raw materials, water and energy) that, when end-up as waste, have negative impacts on the environment. As an alternative, the model of circular economy (CE) has been proposed in which products and services are designed in such a way that their components, materials or waste can be reintegrated into the system.

Circular product design makes the extension of product life possible through the loops of maintain/prolong, reuse/redistribute, refurbish, remanufacture and recycle. Materials in the product should be selected and designed to maintain their purity and the product structure should allow reuse, disassembly and reassembly, among others. At the end-of-life, the product, its parts and materials will again become resources. Components are reclaimed in remanufacturing and materials continue their life through recycling.

The concept of CE is complex, and it includes business, technical, legislation and other aspects that all are connected. The literature on circular design focusses on many other things than the technical design and engineering, and, in fact, does not discuss much about the design process and details of technical design in CE. How the requirements are set and what competencies the designer is expected to have blur the boundaries between technical design and other operations, such as business and service planning.

The report is organised as follows. After the introduction in Section 1, the design for X approach is discussed in Section 2. In Sections 3 and 4, respectively, the circular design and the guidelines and strategies for developing circular products are discussed. The frameworks and tools supporting circular design are highlighted in Section 5. Various competencies required by designers are listed in Section 6. Some of the identified challenges in design for CE are discussed in Section 7, and in Section 8, the findings are discussed and conclusions are made.

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Espoo 13.1.2021

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Preface

Environmental awareness and the concern about diminishing resources are slowly and inevitably coming to the consumer business and the business-to-business field. One concrete evidence of this has been the increasing interests in the concept of circular economy. While circular economy, i.e. business relying on circulation of products, components, parts and materials, is still not dominating, its value and importance are growing. The overall concept of circular economy is far from being simple and straightforward, as also the findings of this review report on circular design show, and truly assimilating the concept and acting accordingly take time. However, as with many other new trends, the early adopters often take their share of markets and win.

This review report focuses on product design aspects in circular economy. The report concludes that there is plenty of information available concerning circular economy and design for circularity. Another general finding is that as the overall concept of circular economy is complex and the nature of it is recursive and looped, similarly design, as one phase of the overall process, is complex. In addition to bringing new requirements for the product design, the circular product process increases the need for engineers and designers to understand the business environment and the whole life cycle of the products they are designed for, and even beyond.

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Authors

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1. Introduction

Many of today's products are not designed by considering the sustainable usage of finite resources and environmental effects. The current take-make-dispose economy is based on the rapid procurement and satisfaction of needs. The production of goods requires a large number of primary resources that, when end-up as waste, have negative impacts on the environment. As early as in 1999, (Tomiyama, 1999) introduced the idea of Post Mass Production Paradigm for decoupling the economic growth from resource and energy consumption and waste generation. More recently, this has been realised in the model of circular economy (CE), in which the conservation of value is the top priority (Steiniger & Hansen, 2018).

The CE model is a concept about producing products and services by reducing the use of non-renewable raw materials, water and energy, while it promotes their reuse and reintegration into the system (Bovea & Pérez-Belis, 2018). It imagines how we might keep resources in use for as long as possible by extracting the maximum (use and exchange) value from products and materials at the end of each service life. Two key approaches to achieve this are closing resource loops through recycling (at the end of product life) and slowing cycles of resource use (Lofthouse & Prendeville, 2018). To be able to include products in CE, products must be designed in such a way that their materials, components or waste can be reintegrated into the system (Bovea & Pérez-Belis, 2018).

For design, the CE replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals that impair reuse and aims for the elimination of waste through the superior design of materials, products, systems and business models (Moreno, De los Rios, Rowe, & Charnley, 2016). Circular product design elevates design to a systems level, strives to maintain product integrity, is about cycling at a different pace, explores new relationships and experiences with products, and is driven by different business models (Van den Berg & Bakker, 2015).

A circular product design makes the extension of product-life possible through the loops of maintain/prolong, reuse/redistribute, refurbish, remanufacture, and recycle (Steiniger & Hansen, 2018). Materials in the product should be designed to maintain the purity and the product structure should allow reuse, disassembly and reassembly. Collaborative production and consumption should also be considered in circular design (Chen, 2015). At the end of life, inspired by nature, a product, its part, or material will become a resource within or even outside of the original application. Components are reclaimed in remanufacturing, and materials continue their life through recycling (Medkova & Fifield, 2016).

Designers have the responsibility of defining the product characteristics and its circularity potential, i.e., their reparability, durability, selection of materials, proportion of recycled and renewable materials; their suitability for refurbishment, remanufacture, etc.; establishing the link to new business models and services which are required such as maintenance, repairing, reuse and reverse logistics; and other services like sharing, leasing and renting. Designers have the role of meeting peoples' needs and developing technically and economically feasible products and services (David Camocho, Vicente, & Ferreira, 2019), (D. Camocho, Vicente, & Ferreira, 2020).

This review report is organised as follows. After the introduction in Section 1, the design for X approach, which lays the bases for many more detailed concepts, is discussed in Section 2. Then, the circular design and the guidelines and strategies for developing circular products are discussed in Sections 3 and 4, respectively. The frameworks and tools supporting circular design are highlighted in Section 5. Furthermore, various competencies required by designers are listed in Section 6. Some of the identified challenges in CE and in design for CE are discussed in Section 7. In Section 8, the findings are discussed and conclusions are made.

2. Design for X

The implementations of design for assembly and design for manufacture led to enormous benefits including simplification of products, reduction of assembly and manufacturing costs, improvement of quality, and reduction of time to market. In addition, the environmental concerns (Olesen & Keldmann, 1994) requires that disassembly and recycling issues should be considered during the design stages. Therefore, researchers begin to focus their attention on design for environment, design for recyclability, design for life cycle, and so forth. These studies are sometimes referred to as Design for X, or DfX. (Marxen et al., 2001).

(Marxen et al., 2001) provided detailed information about the concepts, applications and perspectives of DfX in manufacturing. Design for assembly and design for manufacture make a product easier to produce with lower costs. Design for disassembly, design for recyclability, and design for life cycle make the designer plan ahead for product processing after its useful life. Design for environment focuses on environmental safety and health related issues and thus can help reduce the indirect cost of a product. Quality, maintainability and reliability can also be assured by design and process controls rather than by expensive testing, diagnostics and rework. Although the authors didn't mention about circularity, however, designing products according to the DfX will be in line with CE concept. It is important to note that here CE refers to the circular economy and not concurrent engineering. Design for life cycle and e.g. the concept of product life synthesis have been discussed thoroughly also in (Andreasen, Hansen, & Cash, 2015).

According to (Alting & Legarth, 1995), two design strategies deserve special attention, design for energy savings (DfES) in the use phase and design for disassembly (DfD), because of their widespread implementation, and because they take action on some of the most important environmental issues, namely the depletion of energy resources, the pollution from the production of energy, the preservation of pools of non-renewable resources through recycling, and the pollution savings from using recycled materials. The fact that so many of the devices we use today are active all 24 hours of the day, puts focus on stand-by consumption. Although stand-by or idle mode effect consumptions are much lower than in-use effect consumptions, the total stand-by energy consumption make up a great part of the energy used by the product. Similarly, the possibility to disassemble products into recyclable fractions and the issue of material quality preservation is the heart of the matter in optimal recycling. DfD methods and tools focus on product structure in order to ease disassembly (decrease disassembly time) and to put together product parts that require the same route of disposal.

Design for disassembly is a comprehensive and essential strategy within the circular product design model. A product designed to be easily disassembled brings about various benefits throughout the product's life cycle, including efficiencies in manufacturing and assembly, maintenance or servicing, and recovery at end-of-life both through remanufacturing and recycling. (Franco, 2019).

(Bocken, Pauw, Bakker, & Grinten, 2016) proposed design for reliability, which relates to products designed with a high prospect of no failure operation throughout certain time if the manufacturer’s use and maintenance instructions are observed. In addition, design to dematerialise, reducing the amount of materials required but still sustaining the core functionality, should be taken into account. Dematerialisation also means inventing brand new solutions with no or less material required.

Furthermore, the end-of-life (EoL) options (refurbishing, remanufacturing, recycling, etc.) aimed for a product has strong effects on the way the disassembly options can be carried out. For example, if a product is designed for recycling EoL option and the product does not include hazardous materials, then the disassembly operation can be carried out through destructive disassembly methods such as the shredding method. On the other hand, if a product is designed for remanufacturing and reusing EoL options, then disassembly operation should be non-destructive. (Avdan, 2016)

3. Circular design

A single product's life cycle from raw material extraction to the user phase comprises a complex and comprehensive resource and energy supply chain, which lead to pollution and emissions. In linear business model, products are disposed at the end-of-life phase as waste. Then, producing a new single product requires the same amount of resource and energy consumption. Alternatively, circular business model aims at reducing resource and energy consumption via a repetitive reutilisation of resources (Avdan, 2016).

As opposed to linear design, the circular design is described as the improvements in material selection and product design (standardisation and modularisation of components, purer material flows, and design for easier disassembly) (Ellen MacArthur Foundation, 2013). Circular product design aims to propose two essential considerations when a product is designed. First, product design should encourage the consumer to use the product for a long(er)-term. For example, durability and/or upgradability are some of the essential design strategies and features of a product to make this happen. Second, product design should enable to extend lifespan of used products. In this sense, easy disassembly and reassembly features of a product are needed (Avdan, 2016). Materials should be safe and recoverable so as to be circulated in the system, and that products are designed for reuse, disassembling and recycling. Circular design should not only focus on the product itself but also the business model and the social factors around it (Chen, 2015). Furthermore, it is recognised that the design of circular products will have considerable impact on the design of a product due to the new requirements to be fulfilled, especially in relation to functional, emotional, aesthetic and economic considerations (Bakker, Wang, Huisman, & Den Hollander, 2014).

The main characteristics of circular products are shown in Figure 1. Circular product design enables products that are: future proof (last long and use long), and that can be disassembled, maintained (products), remade (components), and recycled (materials).

In the CE model, every circle returns to an earlier point in the product life cycle, which is effectively the reuse of a product, component or material (see Figure 1). Direct reuse by reselling/redistributing where a product is used for the same purpose without any changes is part of a business model and not that of product design, although such a business model will make longevity of products more attractive (Van den Berg & Bakker, 2015).

According to The Great Recovery research (Redesigning the Future), conducted by the Royal Society for the Encouragement of Arts, Manufacturers and Commerce (RSA), four models can be distinguished for circular design (RSA, 2016), see Figure 2:

1. *Design for longevity* promotes long life and reliable products that can be easily dismantled for upgrade or repair by the user.
2. *Design for leasing/service* changes the product ownership into a product-as-a-service business model. As the product and, therefore, the material ownership stays with the producer or manufacturer, the designed products are durable and long lasting in order to maximise efficiency.
3. *Design for reuse in manufacture* aims at the return of old products or their components back to manufacturers for an upgrade on faulty or obsolete parts replacement, to be subsequently resold.
4. *Design for material recovery* recaptures materials and products to be reprocessed and recycled into new materials.

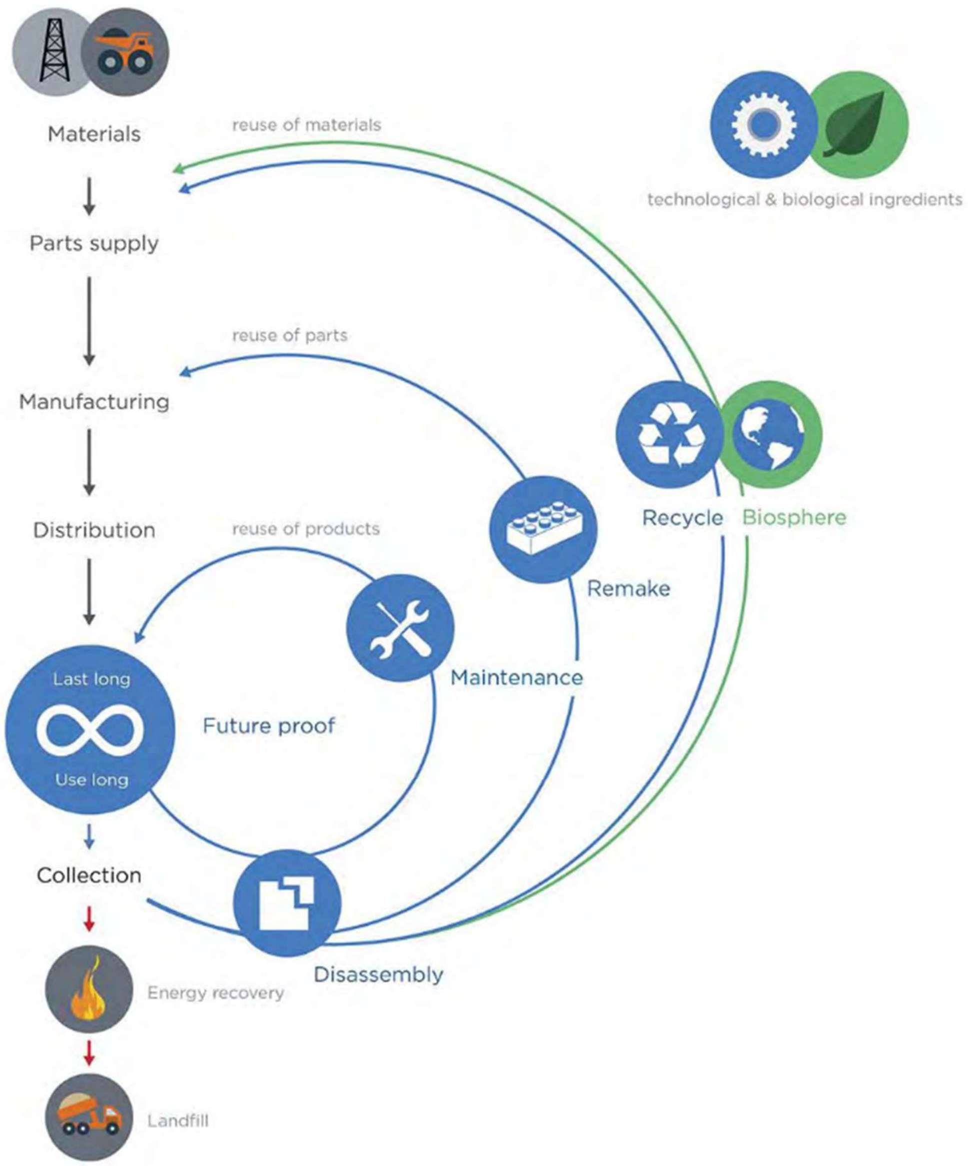

Figure 1: Circular product design model (Van den Berg & Bakker, 2015).

While designing for a CE, (Moreno et al., 2016) presented the following ten recommendations:

1) Design for “systems change” when considering any circular design strategy.
2) Design by identifying the new circular business model that your product/service is being designed for.
3) Design by thinking of revolutionising the world: circular design goes beyond doing less bad.
4) Design for multiple cycles (short and/or long) and not only with end-of-life in mind.
5) Design by thinking in living and adaptive systems.
6) Design with different participants in the value chain, including your final user, and always keep him/her/it in mind.
7) Design by considering value in a broader view, not as a price tag on a shop shelf, but as an asset.
8) Design with failure in mind: it is better to test and prototype as many times as possible.

9) Design knowing where each material and part comes from and where each material and part goes to.

10) Design with "hands on" experiences that foster a call for action.

Figure 2: The Four Design Models (RSA, 2016).

4. Guidelines and strategies for circular design

According to (S. Shahbazi, Jönbrink, Jensen, Pigosso, & Mcaloone, 2020), it has been estimated that approximately 80% of the sustainability performance of a product over its life cycle is defined in the early stages of the product design and development process. If circularity is to be emphasised in the product's life cycle so that it can be reused, repaired, remanufactured or recycled, it has to be taken into account in the early design stages.

To help product designers implementing circular design approaches, (Van den Berg & Bakker, 2015) developed a guideline list (also called circular design tool by (Ghoreishi & Happonen, 2020)) as shown in Figure 3. Disassembly is part of every circle and thus represented by a line on the left side extended downwards and is divided into non-destructive and destructive disassembly options.

In addition, (Andrews, 2019) listed the following guidelines that are intended to overcome barriers to the CE implementation and designers are encouraged to:

- Design for maintenance, repair and upgrade to extend life.
- Design for disassembly to facilitate separation of parts for recycling and/or reuse.

- Consider joining methods – ideally avoid adhesives and use mechanical and/or smart fixings.
- Minimise materials mixing unless performance is compromised.
- Dematerialise – use less material without compromising performance.
- Use materials that can be recycled easily – consider alternatives to composites unless performance is compromised (Ellen MacArthur Foundation, 2013).

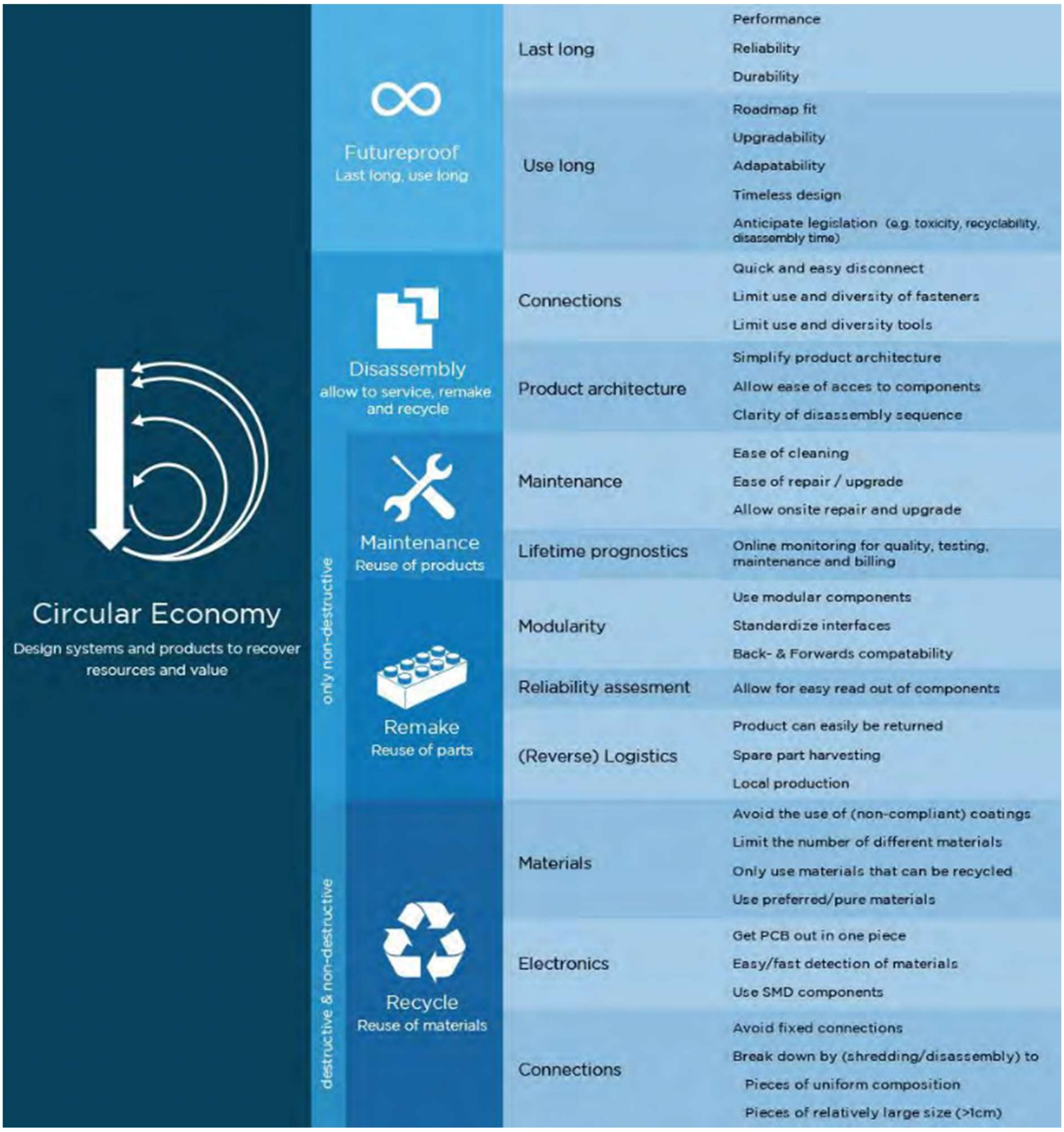

Figure 3: Guideline list overview (Van den Berg & Bakker, 2015).

Furthermore, (Bovea & Pérez-Belis, 2018) collected from the literature 46 design guidelines in the DfX context, and grouped them into the following circular design guidelines:

- Extension of life span, (e.g. timeless design, adaptability, upgrading).

- Disassembly (connectors & product structure), (e.g. use standard joints, minimise the number of joints, adopt modular design).
- Product reuse, (e.g. minimise parts that require frequent repairs/replacements);
- Components reuse, (e.g. use standardised components).
- Material reuse, (e.g. use materials compatible for recycle).

Products and components can only be recirculated in a CE when they are designed for circulation at the design and development phase. In order to support companies in designing circular products at the product design and development phase, (Sasha Shahbazi & Jönbrink, 2020) presented a set of 28 generic circular design guidelines for 15 different circular strategies. In addition, the effect of the guidelines on a specific circular strategy is highlighted. The guidelines have been designed to be used by the key stakeholders working on product design and development, such as designers, engineers, research and development professionals, and product owners. The guidelines are generic and can be tailored and detailed depending on the product type, material used, product development process, environmental management system, environmental and circularity goals, the adopted business model innovation, and the circular strategies and production system of companies.

The various guidelines are affecting each other as well as the circularity strategies, therefore, the guidelines must be used comprehensively as a whole, and then, specific design guidelines should be referred (if needed). Changing product design to fit the business model innovation is the best approach to move towards CE. In the next paragraphs, some of the strategies for designing circular products are presented.

(Alting & Legarth, 1995) discussed the following design strategies for various life cycle phases:

- Design strategies reporting to the pre-manufacture phase deal with the environmentally conscious selection of materials and components.
- Design strategies reporting to the manufacture phase deal with either improving process performance or with reducing overhead.
- Design strategies reporting to the transportation phase are either directly connected to the product, such as design for low volume or weight and the choice of environmentally friendly packaging materials, or to operational practices, such as the improvement of transport logistics. Since the energy consumption (and cost) of many transportation processes are related to the weight or volume of the product, reducing these will result in a more environmentally friendly product.
- Design strategies reporting to the use phase deal with increasing functional efficiency, adaptation to individual use patterns, and reduction of the consumption of consumables, primarily energy.
- In designing for the disposal phase, two major principles prevail. Firstly, adaptation to current and future disposal systems. This involves the discipline of design for disassembly, which enhances recovery efficiency. Secondly, the issue of material quality preservation is essential. It is well known that the removal of impurities in the reclamation of metals is associated with the larger part of the environmental burdens. Further, high purity is absolutely essential in the direct recycling of plastics.

To counter obsolescence and keep a product as close as possible to its original purpose (product integrity), (Medkova & Fifield, 2016) identified the following six strategies for circular product design based on previous studies. The application of these strategies for smartphone (modular product), are presented in the study by (Schischke, Proske, Nissen, & Lang, 2017).

1. *Design for product attachment and trust*, sometimes called 'design for emotional durability' is regarded as the most challenging, aims at responding to an emotional obsolescence by creating long lasting products that people will love and trust.
2. *Design for product durability* creates products resistant to wear and tear, in other words, physically durable products. Here, the material choice is crucial in overcoming functional obsolescence.
3. *Design for standardisation & compatibility* fights against systemic obsolescence by designing product's parts and interfaces suitable for other products and aims at multi-functionality and modularity.
4. *Design for ease of maintenance and repair* counters functional obsolescence by ease of maintenance to keep a product in working condition, and non-challenging reparability and replacement of broken parts to extend the end of the life.
5. *Design for upgradability & adaptability* avoids systemic obsolescence by maintaining product usability for a long time by upgrading its value and performance, and at the same time, by adaptation and modification towards the changing needs of a user.
6. *Design for dis- and re-assembly* also avoids systemic obsolescence by designing products and their parts to be eventually easily separated and reassembled. This strategy has a big impact on component and material reuse and remanufacturing.

Building on previous studies, (Bocken et al., 2016) introduced the following two fundamental strategies towards the cycling of resources:

1. Slowing resource loops: Through the design of long-life goods and product-life extension (i.e. service loops to extend a product's life, for instance through repair, remanufacturing), the utilisation period of products is extended and/or intensified, resulting in a slowdown of the flow of resources.

   Design for long-life products is associated with design for attachment and trust, design for reliability and durability. Whereas, design for product-life extension is associated with design for ease of maintenance and repair, design for upgradability and adaptability, deign for standardisation and compatibility, design for dis- and re-assembly).
2. Closing resource loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources.

These two approaches are distinct from a third approach towards reducing resource flows:

3. Resource efficiency or narrowing resource flows, aimed at using fewer resources per product.

(Steiniger & Hansen, 2018) identified nine strategies for the implementation of circular product design of the smartphone, these are:

1. Building a relationship with the product.
2. Enabling reparability of single components.
3. Establishing repair support systems.
4. Using spare parts from old devices.
5. Coordinating the product development.
6. Opening the software code.
7. Financing by private investors.
8. Strengthening of current cooperation agreements.
9. Network extension.

The strategies are of different disciplinary nature that point to the complexity and multidisciplinary of dealing with challenges resulting from the implementation of a circular product design.

(Pozo Arcos, Balkenende, Bakker, & Sundin, 2018) presented six design strategies for the functional recovery operations, like repair, refurbishing or remanufacturing:

1. Preventive maintenance.
2. Upgrading (hardware).
3. Repairing - corrective maintenance and breakdown maintenance.
4. Refurbishing or reconditioning.
5. Part harvesting.
6. Remanufacturing.

Pozo Arcos et al. also provided some guidelines to ease the operations of cleaning (e.g. minimise geometric features that trap contaminants), product diagnosis operations (e.g. make wear of parts detectable and visible), disassembly and reassembly (e.g. avoid the need for specialised disassembly procedures), and storage (e.g. use identical or grossly dissimilar parts). There is little information on how to use these guidelines or which guidelines should be prioritised over the others in case of a trade-off between them.

(Urbinati, Latilla, & Chiaroni, 2018) focused on the product design practices that can be conceived in CE business models along two major dimensions: (1) the value network, i.e. the ways through which companies interact with suppliers and reorganise their own internal activities, and (2) the customer value proposition and interface, i.e. the implementation of the circularity concept in proposing value to customers.

- Product design practices at value network dimension consist of: *design for reused*, *design for repair and maintenance*, *design for redistribute or reuse*, *design for refurbish*, *design for remanufacture*, *design for disassembly and reassembly* and *design for recycling*.

- Product design practise at customer value proposition and interface dimension include: *design for durability*, *design for quality*, *design for reliability*, *design for esthetical-longevity*, d*esign for customisation* and *design for customer's attachments*.

5. Frameworks and tools supporting circular design

According to (Van den Berg & Bakker, 2015), the various circular design related guidelines can be translated into a spider map (Figure 4) for a more detailed tool to be used in the design process. Words are placed along the axes to show an increase of circularity, i.e. describing aspects that are likely to aid in optimal resource usage and recovery. The tool can be used in the first phases of the design process when no detailed information is available yet. It will enable the discussion of the ambitions for a new project, to show a way towards circular product design, to agree on terminology and to compare with other products.

To help designers to understand which is the business model they are designing for, (Moreno et al., 2016) mapped out five circular design strategies according to the circular business models and their position in the value chain, see Figure 5. The framework provides design practitioners with a holistic view of how to approach circular design, not only from a product perspective but by taking into account the relevance and importance of the surrounding business models and how to integrate them with the design process. In addition, the framework acknowledges the role of policy and regulation in enabling circular business models. The design strategies are:

- *Design for circular supplies*: This strategy focuses mainly on the biological cycles and refers to thinking of “waste equals food” in which resources are captured and returned to their natural cycle without harming the environment.
- *Design for resource conservation*: This strategy focuses on both the technical and biological cycles and uses a preventative approach in which products are designed with the minimum of resources in mind.
- *Design for multiple cycles*: This strategy focuses on both the technical and biological cycle and refers to design aimed at enabling the longer circulation of materials and resources in multiple cycles.
- *Design for long life use of products*: This strategy focuses on the technical cycle and refers to extending the utilisation of a product during its use through extending its life and offering services for reuse, repair, maintenance and upgrade [23], or by enhancing longer-lasting relationships between products and users through “emotional durable design”. Furthermore, changing the ownership of products through services could enhance longer utilisation of products and, therefore, move to a sharing system.
- *Design for systems change*: This strategy covers the whole spectrum of value creation for both biological and technical cycles and refers to design thinking in complex systems as a whole and between its parts to target problems and find innovative solutions.

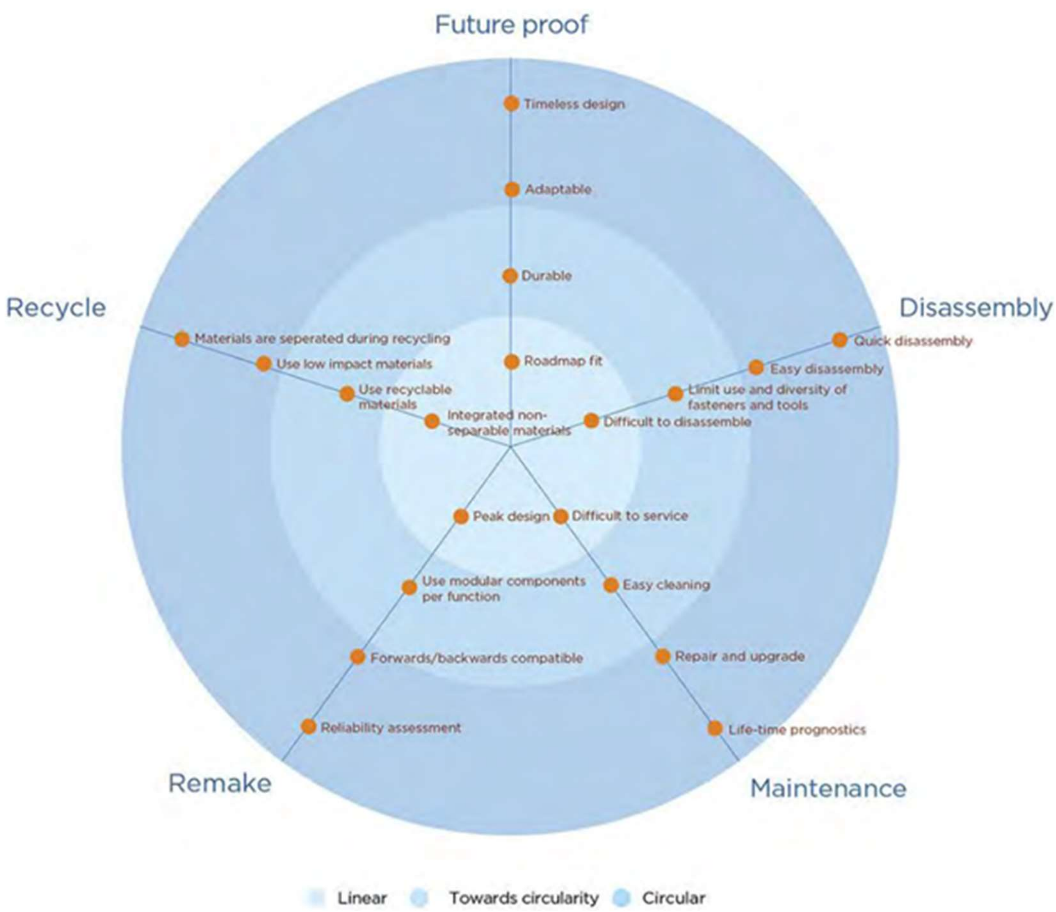

Figure 4: Spider map (Van den Berg & Bakker, 2015).

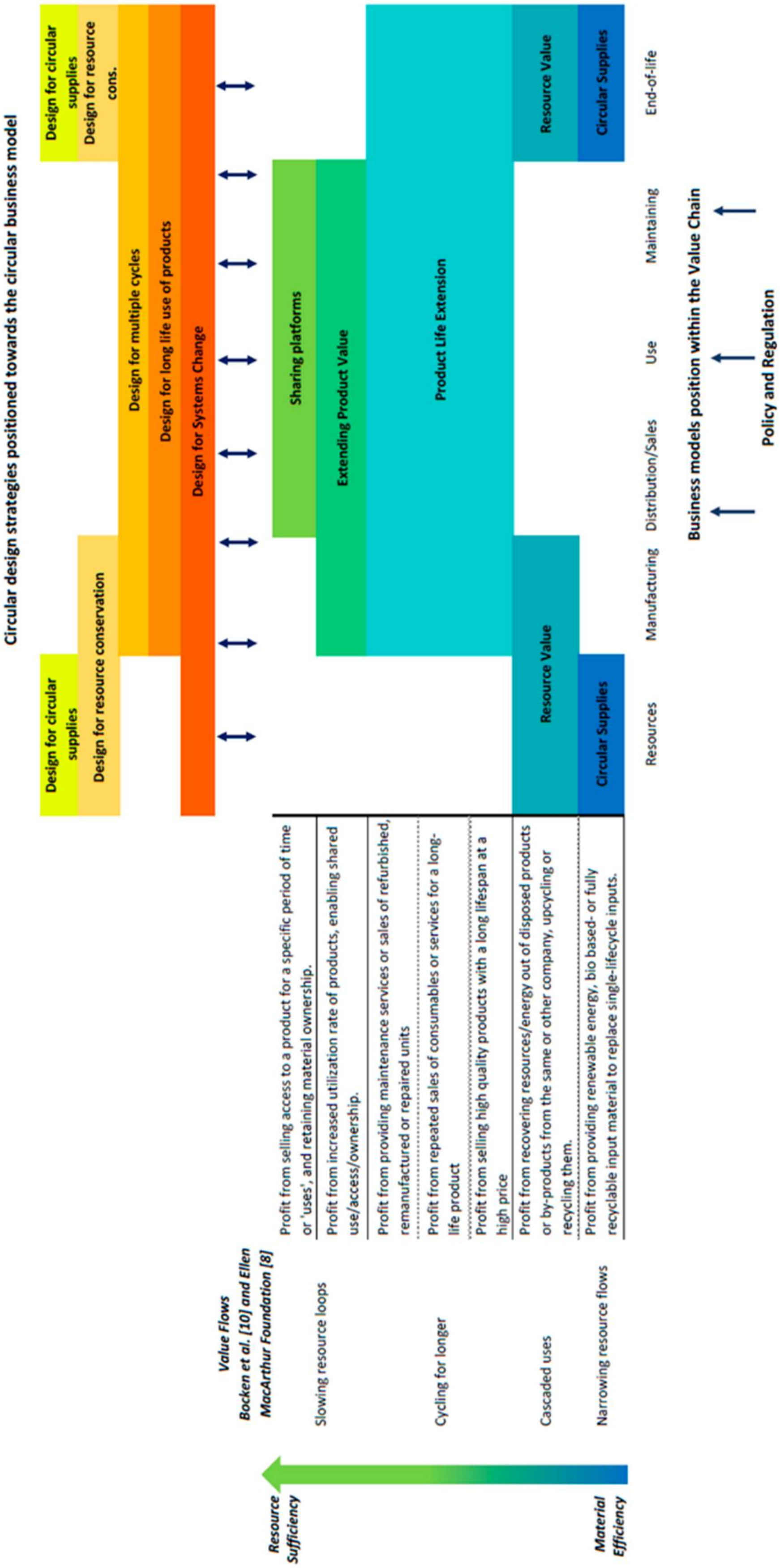

Figure 5: Circular design framework: circular design strategies mapped out against the circular business model archetypes and their value creation (Moreno et al., 2016).

RSA (2013, 2014) created a tool for designers, the Circular Network (see Figure 6), in which they mapped different stakeholders engaged during a product's life cycle that should be involved in the dialogue on changing design towards circularity. The Circular Network tool divides these players into segments of a circle, which emphasises the equality and importance of all stakeholders' collective views and insights. These general segments are: consumers and users, design, academics and education, investors, policy makers, resource management, material experts, manufacturers, and finally brands and companies. The segments are then split into more detailed sub-segments. (RSA 2013, 2014)

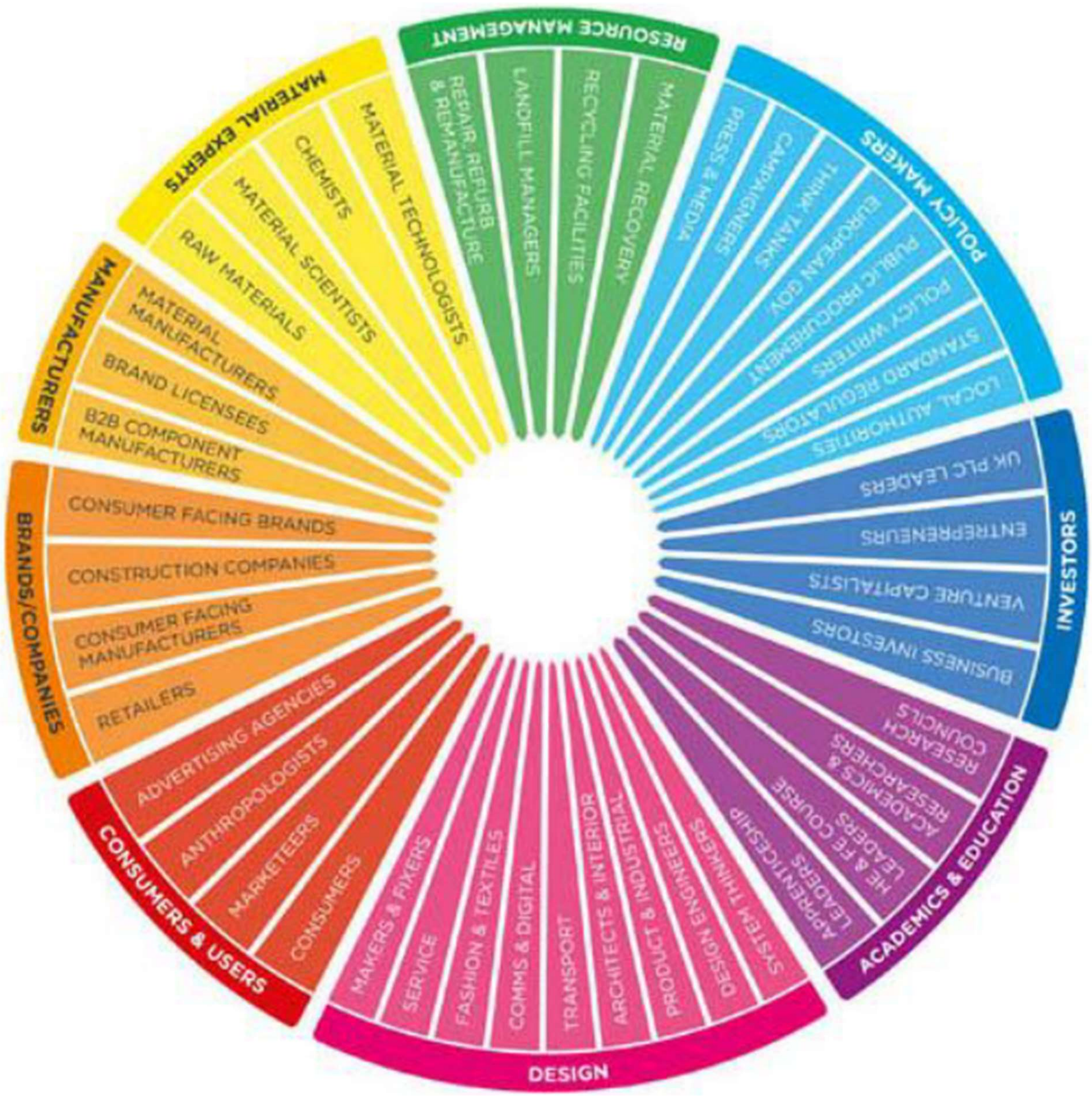

Figure 6: The Circular Network (RSA, 2016).

(Moreno Beguerisse, Ponte, & Charnley, 2017) created a circular design tool from a taxonomy of design strategies related to CE aspects. A pair of shoes were used as an example on how the circular design tool can be used. The taxonomy consists of circular design aspect (e.g. resource conservation, life cycle (end-of-life), whole system design, customer, and development), DfX approaches (e.g. design for energy conservation, design for users, etc.) and strategies (e.g. use clean energy consumption, allow reusability).

(Stijn & Gruis, 2020) developed a design framework to support the design synthesis of circular building components. The framework supports designers as follows:

1) It provides designers all the design parameters which should be considered when making a circular design.
2) It gives designers an extensive list of circular design options for each parameter.
3) Through the design templates, in which selected design options can be systematically mixed and matched, the framework supports the synthesis of a cohesive and comprehensive circular design.

(S. Shahbazi et al., 2020) developed a circularity assessment tool to be used in the early phase of product development process, i.e. in planning and concept development, to assess product designs and concepts in terms of their circularity potential. The tool has been designed to calculate a *total circularity potential score* for at least two concepts, so that they can be compared in terms of circularity. The tool can also be used for a single concept or product to identify hotspots and improvement potentials. The lower the *total circularity potential score* is, the better the concept is in terms of circularity. For example, as shown in Figure 7, Concept B with lowest score among the three concepts is the best option. This tool is developed especially for internal communication support for decision making in the early product development process, and the results should not be used for external communication.

Some authors argued that although methods and tools for a large variety of the design strategies already exist (e.g. design for recycling, design for remanufacturing and design for end-of-life), they might need to be adapted to a circular design context (Bakker et al., 2014). Furthermore, (Laurenti, Sinha, Singh, & Frostell, 2015) argued that information technology and computer-aided design (CAD) tools should be refined in order to support circular design. Some of the proposed features include: guide user behaviour towards increased product lifetime and reuse; design in a way that decreases material stock in the use phase and considering material; and design concept choices so that material flows are kept clean. (Pigosso & McAloone, 2017)

6. Design competencies in circular economy

(Rios & Charnley, 2016) listed the following design skills necessary for creating products for different business models: understand logistics and distribution process, understand the service experience and how to design services, understand user expectations and perception of value, understand factors of the use experience, understand product wear by use, assess material physical and chemical properties, understand engineering functions of the product, understand failure mode and maintenance procedures, understand processes for reverse and re-manufacturing, and solve aesthetic and structural problems with limited supplied components.

State your selected circularity goals: General design guidelines	Improtance to developing the product Really important (3) Moderately important (2) Slightly important (1) Not important (0)			Level of fulfillment (1) *yes*, the guideline has been completely fulfilled by this concept (3) *somehow*, but can be improved (5) *no*, the guideline has not been fulfilled by this concept and it has to be			Circularity Potential Scores 15: Vital and imperative 10 and 9: Improvement are necessary 6 and 5: Potential circularity improvements 3, 2 and 1: No change required 0: Not a concern		
	Concept A	Concept B	Concept C	Concept A	Concept B	Concept C	Concept A	Concept B	Concept C
Focus mainly on functionality and quality performance	2	3	3	1	3	5	2	9	15
Think about activity supports in the operational stage	2	2	2	1	5	5	2	10	10
Focus to fulfill the customer's requirements and value creation	3	2	3	1	3	3	3	6	9
Try to use digitalisation, ICT and IoT solutions	3	3	3	1	3	3	3	9	9
Make it easy to inspect the product and components	2	2	2	1	3	3	2	6	6
Make it easy to clean the product and components	3	1	3	1	5	3	3	5	9
Make exchanging of faulty components easily accessible	3	1	3	5	5	5	15	5	15
Make it easy to dismantle the product nondestructively	3	1	3	3	3	3	9	3	9
Think about boundary management	2	1	3	5	1	3	10	1	9
Think about incumbent configuration	3	1	3	1	1	3	3	1	9
Think about complementary capabilities	3	1	3	1	5	3	3	5	9
Design using renewable materials	1	1	3	1	5	3	1	5	9
Design using recyclable and secondary (recycled) materials	2	3	2	1	1	3	2	3	6
Consider toxicity and other environmental aspects of materials	2	2	3	5	1	3	10	2	9
Favour cleaner production, processes, machines and equipment	2	1	1	1	1	1	2	1	1
Treat production (pre-consumer) wastes appropriately	3	3	1	5	1	5	15	3	5
Design for reduced energy consumption and usage of renewable energy	2	3	1	3	1	5	6	3	5
Design standardised components across different products and models	2	3	1	3	1	5	6	3	5
Design standardised tools required across different products and models	3	1	1	5	1	5	15	1	5
Use durable and robust components and materials	3	1	1	3	1	5	9	1	5
Design in modular construction	3	2	2	3	1	5	9	2	10
Provide manuals and documentation	2	2	2	5	1	5	10	2	10
Make spare parts and exchanging components easily available	1	1	2	3	3	5	3	3	10
Consider timeless design, emotional attachment and compatibility	1	2	3	3	3	5	3	6	15
Investigate current and upcoming laws and regulations	1	1	3	3	3	5	3	3	15
Use joints and connectors that can be easily opened and closed multiple times	1	3	3	5	1	3	5	3	9
Minimise the number of different incompatible or dissimilar materials	3	2	2	5	3	3	15	6	6
Make it easy to identify the materials and relevant information	1	3	3	5	1	3	5	3	9
Total Circularity potential Score with inclusion of the effect (the smaller the better)							**174**	**110**	**243**

Figure 7: Circularity assessment tool (S. Shahbazi et al., 2020).

By interviewing design professionals, (Sumter, de Koning, Bakker, & Balkenende, 2020) identified seven competencies (knowledge, skills, attitudes) that designers need to have to successfully design products and services for CE. These are:

- *Circular impact assessment*: Estimating the environmental impact of circular offerings on a system level over multiple use cycles to support decision-making during the design process.
- *Design for recovery*: Incorporating recovery strategies during the design process while taking into account multiple use cycles.
- *Design for multiple use cycles*: Foreseeing the consequences of prolonged use and multiple use cycles.
- *Circular business models*: Concurrently developing the circular product, service, and business model.
- *Circular user engagement*: Engaging users in the use and the (end-of-use) return of products.
- *CE collaboration*: Identifying, mapping, facilitating, and managing the collaboration between external stakeholders in operationalising a circular business model.
- *CE communication*: Telling coherent stories about the circular offerings.

(Sumter, Bakker, & Balkenende, 2018) mentioned about the anticipatory and “planning-ahead” competencies that are needed to design a product that must stay relevant, desired, and cost-effective over multiple use cycles.

7. Challenges in circular economy and circular design

The circular design model is described as the improvements in material selection and product design (standardisation and modularisation of components), purer material flows, and design for easier disassembly compared to the typical targets in the linear economy design model. Circular product design enables products that are future proof (last long and use long) and that can be disassembled, maintained (products), remade (components) and recycled (materials). Both the design of product and the design of materials are focused in the circular design approaches.

Some materials like pure steel, aluminium, copper can be recycled indefinitely, however, other materials (such as paper, wood and plastics) can only make it through the process a limited number of times before they are disposed in landfill or incinerated. This can also happen with metal because of hard-to-separate impurities or because they are generally mixed into alloys. A typical soda can, for example, consists of two kinds of aluminium which are melted together during recycling, resulting in a weaker product (Rammelt & Crisp, 2014). The fewer the materials in a product, the easier the recycling is, since less separation work is involved.

(Reh, 2013) explained the connected life cycle of process and product. Producing innovative high-quality products require also the combination with an innovative sustainable process to assure successful economic and ecologic performance of a new industrial mass transforming plant. The re-user industries have to adapt their own processes to cope with the somewhat minor quality recycled resource flows accordingly. All these steps additionally need longer planning and realisation periods. Recycling of all components of used products with high recycling rates will remain a dream. Methods for selecting the most valuable components for recovery need to be established.

Design strategies influencing the choice of material and manufacturing process and product structure alone cannot warranty the success of the recovery operation. It is clear that the necessary business model to allow for an economically successful process has to be put into place, and set in parallel with the design strategies to define distribution, logistics and management of the second life products, for instance. In addition, CE requires a more complex infrastructure than the one required in a linear one in terms of supply chain, logistics, marketing, recovery facilities and labour. Furthermore, there should exist a market that would demand for reused and long-life products without which these strategies would not make sense. (Pozo Arcos et al., 2018).

The ultimate goal of design for product integrity is to minimise and ideally eliminate environmental costs by preserving or restoring the product's added economic value over time. Extended product lifetimes, however, do not always result in a net reduction of environmental load. Over time, newer versions of products may be developed that incorporate more efficient technologies. From that moment on, the environmental impacts that arise from the prolonged use of a product may become larger than the embedded impacts of a more efficient replacement product (Bakker et al., 2014). Therefore, product designers need to understand the ecological consequences of their design interventions.

While it is obvious that three post-use strategies, i.e., reuse, remanufacturing, and recycling, are highly relevant to achieve loop closure, it is enormously challenging to choose "the right" strategy (if at all) during the early design stage and especially at the single component level. One reason is that economic and environmental impacts of adapting these strategies are not explicit as they vary depending on the chosen business model and associated supply chains (Lieder et al., 2017). In addition, product attachment and the emotional bonding may postpone product replacement (extended-use), however, this would require high level of customisation both at the customers' orders level and manufacturing processes level, resulting in additional costs. Similarly, changes in technology, products and markets are dynamic, so should be the circular design strategies, policies, and processes (Bakker et al., 2014).

A fully functional smart phone with a crack in the screen may be considered obsolete (and thus in need of immediate repair) by someone who highly values aesthetics, whereas it may seem in perfectly good working order to someone less concerned about the product's appearance. The subjective nature of obsolescence can make it difficult for designers to predict and determine the best design approach.

The implementation of EoL options, particularly refurbishing, remanufacturing and recycling, might require extra stakeholders during reutilisation process such as recycling centres, a new production area for remanufacturing operations and/or a logistic provider for take-back operations. These new stakeholders can provide product designers and developers with valuable and detailed responses about product design and the applicability of EoL options. This means that information should be co-constructed and shared amongst stakeholders properly. (Avdan, 2016).

Some authors argued that although methods and tools for a large variety of the design strategies already exist (e.g. design for recycling, design for remanufacturing and design for end-of-life), they might need to be adapted to a circular design context (Bakker et al., 2014). Furthermore, (Laurenti et al., 2015) argued that information technology and computer-aided design (CAD) tools should be refined in order to support circular design.

Furthermore, it is recognised that the design of circular products will have considerable impact on the design of a product due to the new requirements to be fulfilled, especially in relation to functional, emotional, aesthetic and economic considerations (Bakker et al., 2014).

The development of CE for products is being encouraged to reduce waste and conserve resources. Development is currently limited, and some research discovered that business and policy makers see the main barriers are cultural and market-based and lack of legislation rather than technological or design based. The design guidelines will facilitate development of the CE but implementation can be very challenging. History, culture, economics, geography, politics and user behaviour all influence the potential development of CE. (Andrews, 2019).

8. Discussion and conclusions

This state of the art review study has shown that there is plenty of information available about CE and design for circularity. The challenge of design for circularity has been analysed from several point of views and e.g. numerous design guidelines and strategies for design in CE have been developed and proposed in literature. On the other hand, the challenges resulting from the complexity of the CE model and the fact that the behaviour of the consumers and the dynamics of the markets just cannot be predicted have been identified. In general, the overall concept of CE is complex and it includes business, technical, life cycle, legislation and other aspects that all are connected. This is also evident in the literature for the topic of circular design, which focuses also on many other things, such as material selection and use, product attachment and trust, than technical design and engineering and, in fact, does not discuss much about the design process and details of technical design in CE.

Design as a general concept is used loosely in the context of circular business and CE. Engineering design in general is an action to solve technical problems and requirements that are set by material, technological, economic, legal, environmental and human-related considerations (Pahl, Beitz, Feldhusen, & Grote, 2007). Design, engineering design or product development are just one aspect in the context of circular economy and alone, especially without the underlying business model, do not solve the challenges or guarantee success in the markets. If the technical design process is taken pragmatically, it means designing the technical details and features, and making the production or manufacturing plans according to the set requirements for the product, and using the competencies the designer has for the task. How the requirements are set and what competencies the designer is expected to have blur the boundaries between technical design and other operations, such as business and service planning and the models they are based on.

As the nature of CE is recursive and the products in their different life cycle phases are more closely connected than in linear economy, the role of design and the decisions made during the early phase of the product process have a crucial impact. The concept of front-loaded design or front-end engineering design has shown its importance in projects where large and complex systems are designed and implemented, such as buildings, process plants and complex machines (Williams, Vo, Samset, & Edkins, 2019), (Artto, Ahola, & Vartiainen, 2016). The advantage of emphasising the front-end of the product process is in optimising the flexibility in making decisions and possible changes, when the resources have not yet been tied, and costs caused by the wasted work and materials can be avoided. When the investigations and analyses are done as early as possible in the product process, there is more information available for decision making, which should lead to better decisions and, thus, more successful outcome. With CE, this is emphasised even more, due to the circularity of the process. The decisions made in the early phase affect several cycles and several stakeholders, and have remarkable influence on the overall business model in CE.

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