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Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy

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Abstract: The circular economy is a high priority subject of discussion in the current political and academic contexts; however, practical approaches in relevant disciplines like design are in need of development. This article proposes a conceptual framework for circular product design, based on four multiple loops strategies: (I) design to slow the loops, (II) design to close the loops, (III) design for bio-inspired loops, and (IV) design for bio-based loops**.** Recent literature, notably on life cycle design strategies, the circular economy conceptual model and the European Commission's Circular Economy Package, is reviewed and product design cases illustrating each of the proposed are analysed. The article argues that different 'circular' approaches centred upon the life cycle design phases can provide practical guiding strategies during the design process and thus promote sustainable design solutions for the circular economy within the United Nation's sustainable development goals.

Keywords: Circular economy, Sustainable design, Circular product design, Life cycle design, Close the loops, Slow the loops, Bio loops

1. Introduction

More than one year has passed since two historical moments – the Paris Agreement resulting from COP21 (the United Nations Climate Change Conference), held in December 2015, and the launch of the European Commission's first Action Plan for the Circular Economy Package during the same month. Both are indicative of a revival in international political compromise within the vision of a systematic shift towards sustainable development. There are gaps and weaknesses in the legislative, business and academic frameworks that are intended to implement climate change mitigation and pollution prevention policies and enable a smooth transition to sustainable modes of production and consumption. Practical approaches in relevant disciplines, such as design, are in need of development. This paper intends to contribute to an evolving framework for circular product design. It is hypothesised that existing 'circular' approaches (technical and biological) could be applied to the different phases of life cycle design and thereby play a fundamental role in providing practical guiding strategies for designers and product developers, policy makers and business managers in circular product design.

2. Sustainable design in the circular economy

The circular economy is a concept inspired by authors such as Boulding (1966), Pearce and Turner (1989), Stahel and Reday-Mulvay (1981) and Frosch and Gallopoulos (1989), who argued for the necessity of transforming the traditional 'linear' model of industry (where raw materials enter and products and waste exit the system) into an integrated industrial ecosystem. This closed loop model proposes the optimisation of energy and material consumption, and waste minimisation, where the outputs of one process serve as inputs for other processes (Frosch and Gallopoulos, 1989) to create further value (EC, 2015). More recently, the circular economy has been defined by the Ellen MacArthur Foundation as an economic model "that is *restorative* by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design" (EMF, 2013a, p.22).

In this context, the European Commission Circular Economy Package intends to support a new generation of European businesses, which make and export more efficient and sustainable products and services to customers around the globe (EC, 2015). It proposes a broad set of measures to support the transition from a linear to a circular economy by maintaining the value of products, materials and resources through cyclical, slow, closed and biological loops.

The key proposals, expected benefits and related legislation are summarised in four key action areas of the Circular Economy package: production, consumption, waste management and the market for secondary raw materials. In addition, the package identifies five priority sectors - biomass and bio-based products, plastics, food waste, critical raw materials and construction and demolition - as priority considerations for research.

The transition towards increasingly sustainable modes of production and consumption has led in recent decades to the development of several concepts and guiding strategies for sustainable development (WCED, 1987). In the design context, they have been popularised under the umbrella concept of 'design for sustainability' (or 'sustainable design') (Bhamra and Cooper, 2007), and have gained increasing recognition over the last three decades within academia, albeit encountering barriers to effective implementation at professional and business levels (UNEP, 1998; 2008; 2009).

The relevance of sustainable design should be seen in the context of increased population and unsustainable global consumption patterns. More raw materials are consumed than can be extracted globally, making resource security an urgent problem; many of those based on abiotic resources are expected to be exhausted within the current century (UNEP, 1998; 2008; 2009). As a fundamental aspect of any product, design and material choices can contribute substantially to the depletion of resources, deterioration of ecosystems and human health concerns. These three problems are closely related to three of the six priority areas defined by the United Nations Environment Programme (UNEP) as challenges for the 21st Century: resource efficiency, ecosystem management and harmful substances (UNEP, 2016). The way in which materials are considered in the design process is thus highly significant.

Sustainable design is concerned with the creation of new, added value, eco-efficient products or services that can stimulate the economic competitiveness of industries, while contributing to more sustainable forms of consumption and lifestyle scenarios (Mestre et al., 2009). As a practical product development strategy that meets sustainable development goals, it encompasses ecodesign by improving solutions throughout the product lifecycle, promoting dematerialisation and increasing the eco-efficiency of products (Brezet and Hemel, 1997), as well as other social innovations (Manzini, 2010) and user oriented strategies (EC, 2009).

The Life Cycle Design Strategy (LiDS) Wheel diagram (or Ecodesign Strategy Wheel), which integrates the life cycle approach through a set of improving design options (Brezet and Hemel, 1997), was one of the first 'circular' graphical representations. It was followed by a range of other variations of qualitative and quantitative life cycle design methods and assessment tools (UNEP, 1998, 2008, 2009).

As sustainable development concepts were becoming more widely known and understood, a greater emphasis on product lifetimes was proposed (Cooper, 1994, 2010) focusing on the longevity of a product (van Hinte, 1997, 2004). In subsequent years, sustainable design advanced as a stance that ranged between incremental and radical innovation strategies, addressing areas such as life cycle assessment, product-service systems (PSS), renewable energy and renewable materials, as discussed in UNEP's *Design for Sustainability* global guide (UNEP, 2008).

On a policy level, the *Ecodesign Directive* was first introduced in 2005 by the European Commission (EC). While initially focusing on the energy efficiency of electrical and electronic goods, it was recently revised (EC, 2016) to reflect not only the impact of the use phase and optimisation at end of life (design for disassembly and recycling), but optimisation of the initial lifetime (design for longevity) through strategies such as repairability and durability. The concept has been reflected in both EU legislative frameworks (e.g. EU waste directives) and the UK waste prevention programme (DEFRA, 2013). More recently, the Circular Economy Package (EC, 2015) intended to bridge the Ecodesign Directive and existing waste management strategies with the concept of the circular economy.

In this context, circular product design, in conjunction with circular business model strategies (Bocken et al., 2015), has been proposed as a contribution to design thinking and practice consistent with a circular economy (EMF, 2013a/b). Circular product design is a vision expected to be developed in future decades according to the Circular Economy Package, which highlights the relevance of better product design in a circular economy (EC, 2015).

Reports by the Ellen MacArthur Foundation and the EC Circular Economy Package have given momentum to concepts that were not previously a political or business priority. The former have provided a general framework, while the latter has set out a concrete mandate for the Commission´s current term of office in terms of waste policies and measures to 'close the loop', tackling the environmental impacts along all product life cycle phases (albeit in a compromise with what some academics have long been advocating).

3. Circular product design conceptual framework

Life cycle design emerged in the 1990s as one of the first detailed approaches to *ecodesign.* It includes eight strategies for product development: (I) selection of low impact materials, (II) reduction of materials usage, (III) optimisation of production techniques, (IV) optimisation of distribution systems, (V) reduction of impact during use, (VI) optimisation of initial lifetime, (VII) optimisation of end of life system, and (VIII) new concept development, which were popularised through the Ecodesign Strategy Wheel (Brezet and van Hemel, 1997), and further developed in subsequent years (Vezzoli and Manzini, 2008; Tischner et al., 2000; Charter and Tischner, 2001) serving as the basis for life cycle assessment tools in product design (e.g. ecodesign checklists). This approach proposes intervention in all life cycle phases of a product, in order to improve use of materials and energy, while minimizing toxic emissions.

Product longevity has re-emerged in recent years (Cooper et al., 2015), notably in sustainable design discussions. Having been topical in the 1960s and 1970s due to concerns about planned obsolescence, product lifetimes received little attention in environmental discourse until a New Economics Foundation report proposed: “an environmental strategy is needed which goes beyond recycling, based on longer lasting products” (Cooper, 1994, p.1) in order to gain the necessary reduction in the volume of energy and materials (Cooper, 1994). Increased product longevity can be achieved by “intervening at various points in the lifecycle so that products (and their components) are reused, reconditioned or recycled” (Cooper, 1994, p.4). To this end, Cooper (2000) later advocated design that embraces the principles of (I) durability, (II) reparability, (III) upgradability, (IV) optimised energy and material consumption, and (V) recyclability.

Recycling represents another means by which the throughput of materials can be slowed down. Maximising recycling is commonly described as ‘closing the loop’, a concept popularised as the ‘cradle-to-cradle’ approach (McDonough and Braungart, 1990). It is a biomimetic concept that regards all materials that circulate within industrial and commercial processes as ‘nutrients’ under two primary categories: 'biological ' and ‘technical’. Biological nutrients are organic materials that, at the end of their use, can be safely returned to the biosphere as 'food' for other forms of life and without generating waste; technical nutrients are inorganic or synthetic materials that can be cycled through the production system indefinitely, possibly degraded but without being transformed into waste. Use of toxic chemicals (e.g. heavy metals) or non-recyclable materials is not considered appropriate.

Closely associated with the cradle-to-cradle approach is ‘industrial ecology’ (Frosch and Gallopoulos, 1989), a central principle of which is that societal and technological systems operate within the biosphere and, in order to close material loops, must replicate the natural order - the waste of one industry serving as input for another. This demands “recycling almost everything we use in the same way materials flow in natural systems” (Ehrenfeld, 2008, p. 10). From a product development perspective, industrial ecology “adopts a systemic point of view, designing production processes in accordance with local ecological constraints whilst looking at their global impact from the outset, and attempting to shape them so that they perform as close to living systems as possible” (EMF, 2013a, p. 27).

The efficient and appropriate use of materials is a priority in sustainable design as materials consumption is responsible for the major environmental, economic and social impacts of non-renewable resources (Mestre et al., 2009; Allwood et al., 2011). Careful material selection is a basic requirement for circular product design and its alignment with design strategies for slowing and closing resource loops in the circular economy context (Vogtländer et al., 2015). Sustainable materials or ‘eco-efficient materials’ have six common features: (I) green resource profile; (II) minimal environmental impact during their production; (III) high productivity in use; (IV) minimal hazardous substances; (V) high recyclability; and (VI) high environmental purification efficiency (Nguyen et al., 2003).

Another priority in the circular economy (EMF, 2013a/b) is biomimicry, “innovation inspired by nature” (EMF, 2013a, p. 27). Biomimicry (biomimetics/bionics) is based on the imitation of natural models, systems, processes and other elements in pursuit of solving complex human problems (Merrill, 1982; Benyus, 1997). It maintains three principles: (I) nature as model: the study and emulation of its physical forms, processes, systems and strategies to solve human problems; (II) nature as measure: the use of an ecological standard to judge the sustainability of innovations; and (III) nature as mentor: to view and value nature not based on what we can extract from the natural world, but what we can learn from it (Benyus, 1997). Guiding principles and examples for product design were developed in the 1980s and 1990s, especially under the ‘bionics’ framework (WWF, 1993).

Lastly, the concept of circular product design has been discussed recently under a framework of two types of strategies for the technological and biological cycles of the circular economy: "design strategies to slow resource loops" (e.g. designing long-life products, and design for product-life extension) and "design strategies to close resource loops" (e.g. design for a technological cycle, design for a biological cycle, and design for disassembly and reassembly) (Bocken et al., 2015, pp.310-311).

When analysing all of the above-mentioned concepts, there emerges a clear opportunity to develop practical guiding strategies for designers and product developers; an integrative approach to be applied simultaneously when approaching circularity in design. A multi-concept framework with customised opportunities is thus proposed. The integrative approach intends to (I) address the problem from a complementary, solution-based perspective, approaching it from a sum of different slow, closed, bio- types of solutions as opposed to a partial, singular approach; (II) to allow responsible and creative deliberation of design choices and priorities; and (III) to stimulate creativity in the generation of future circular product design solutions and business models.

4. Circular product design multiple loops diagram – an integrative conceptual approach

There remains a gap in the development, implementation and diffusion of effective product solutions and design scenarios to support the transition to a circular economy. A circular system approach is needed at two levels - technical and biological. In our proposed framework, the levels have been titled 'Design for a Technical Cycle' and 'Design for a Biological Cycle'. Each is subdivided into two additional strategies creating four strategies to be considered within the different phases of the life cycle of a product in order to support designers and product developers (Figure 1).

'Design for a Technical Cycle' is the technical and/or technological use and transformation of material and energy resources, and their design optimisation to the highest possible levels of efficiency. The aim is to minimise material and energy inputs, and emission outputs throughout the whole life cycle of a product or solution, while maximising the highest value proposition for the user and society.

Strategies for the technical cycle are 'slow the loop strategies' and 'close the loop strategies' (Table 1). 'Slow the loop strategies' include slowing material flows in each phase of the life cycle such as design for durability and product life extension (Vezzoli and Manzini, 2008); it also involves more recent developments from the added value user perspective, such as emotionally durable design (Chapman, 2005). 'Close the loop strategies' include strategies such as design for recyclability that enables disassembly and appropriate materials selection. It is important to note that there may be tensions between strategies (e.g. between durability and recyclability) that need to be resolved. 'Design for a Technical Cycle' solutions may be developed at an incremental innovation level, in the short or medium term. They can be implemented within existing business models, optimising their current efficiency levels (see case examples in section 5.1 and 5.2), though more radical solutions may be required in certain cases.

'Design for a Biological Cycle' represents the biological design solutions occurring in (or inspired) by the natural ecosystems, in which materials are cycled in nature over time. Its biological nature represents a level of efficiency close to the intrinsic perfection of the efficiency of nature's closed loop ecosystem (as opposed to the impact-minimising 'Technical Cycle').

'Design for a Biological Cycle' consists of 'bio-inspired loop strategies' and 'bio-based loop strategies' (Table 2). 'Bio-inspired loop strategies' adopt a biomimetic approach and are long established (e.g. Leonardo da Vinci's study of the wing structure of birds for the design of flying machines) and draw upon the science of bionics (i.e. the study of natural systems in addressing human engineering problems). 'Bio-based loop strategies' aim to utilise biological materials that, at the end of their life cycles, can be returned safely to the biosphere in order to provide nutrients to (micro) biological life.

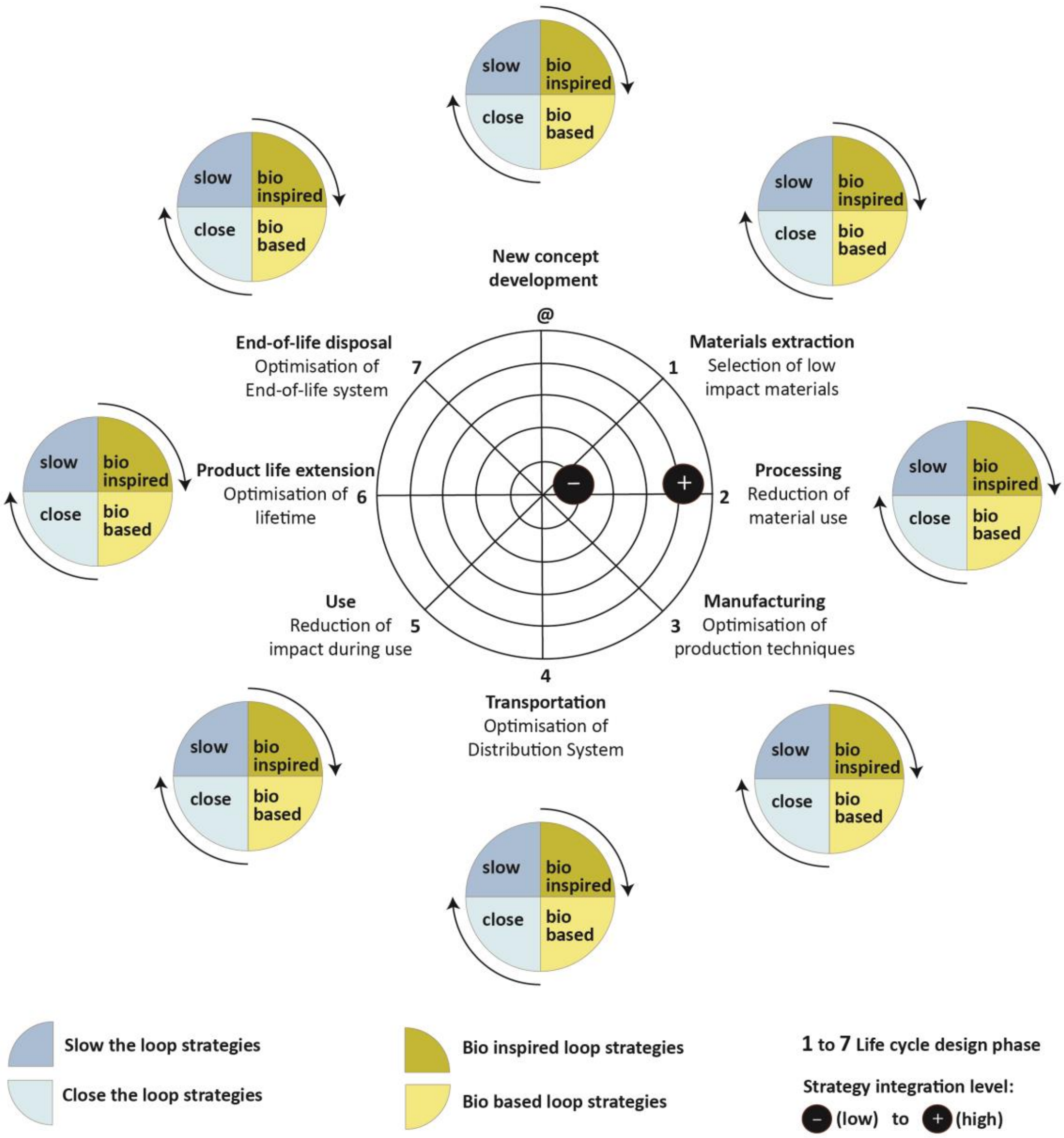

Figure 1. Multiple Loops Life Cycle Design

It is important to note that biological materials still require a balance of energy, nutrients and space, and that mass utilisation of biological materials may lead to their depletion or upset ecosystems. It is therefore essential to consider strategies for the 'Technical Cycles' and the 'Biological Cycles' simultaneously. 'Design for a Biological Cycle' solutions may need to be developed at an advanced innovation level (including radical innovation), to be implemented in the medium or long-term. They may also require new business models for sustainability (see case examples in section 5.3 and 5.4).

Table 1. Life cycle design strategies to slow the loop and to close the loop – Technical Cycle

Life cycle design Strategies	Slow the loop	Close the loop
1 – Selection of low impact materials	a. Cleaner materials b. Renewable materials c. Lower energy materials d. Recyclable materials	a. Recycled materials b. Recyclable materials c. Biodegradable materials d. Lower energy materials e. Photodegradable materials f. Renewable materials g. Cleaner materials
2 – Reduction of material use	a. Reduction in weight b. Reduction in volume (transport)	a. Reduction in weight b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Less production waste e. Fewer/cleaner production consumables	a. Alternative (optimised) production techniques b. Fewer production steps c. Lower/cleaner energy consumption d. Minimal production waste e. Fewer/cleaner production consumables f. Renewable material & energy resources g. Industrial symbiosis
4 – Optimisation of distribution system	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode c. Energy-efficient logistics	a. Less/reusable/ biodegradable (zero waste) packaging b. Energy-efficient transport mode c. Clean & efficient energy logistics d. Elimination of logistics– “do it yourself” (e.g. 3D print at home with starch-based polymers)
5 – Reduction of impact during use	a. Lower energy consumption b. Cleaner energy source c. Cleaner consumables d. Fewer consumables needed e. No waste of energy/ consumables	a. Lower energy consumption b. Clean energy source c. Clean consumables d. Fewer consumables needed e. No waste of energy/ consumables f. Function as service (not product) g. Upgradability (modularity)
6 – Optimisation of initial lifetime	a. Reliability & durability b. Easier maintenance & repair c. Upgradability & adaptability d. Standardization & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation (e.g. emotionally durable design)	a. Reliability & durability b. Easy maintenance & repair c. Upgradability & adaptability d. Standardisation & compatibility e. Modular product structure f. Dis- and reassembly g. Classic design h. Strong product-user relation i. Service for function maintenance (i.e. company takes back end-of-life product, replaces with new)
7 – Optimisation of end of life system	a. Reuse of product b. Remanufacturing/ refurbishing c. Recycling of materials d. Safer incineration	a. Biodegradability b. Remanufacturing/ refurbishing c. Recycling of materials d. Recollection of product for dismantling/material extraction e. Compostability f. Nutritional value (waste=food) g. Photodegradation h. Reuse of product i. Repurpose of product function j. Recollection system for product
@ – Development of new concepts / Product design review / Other design concepts	a. Dematerialisation b. Shared use of the product (ownership) c. Integration of function d. Functional optimisation of product (components)	a. Dematerialisation b. Shared use of product (ownership) c. Integration of function d. Functional optimisation of product (components) e. Function as service (not product) f. Circular business model

Table 2. Life cycle design strategies for bio inspired loop and for bio based loop – Biological Cycle

Life cycle design strategies	Bio inspired loop	Bio based loop
1 – Selection of low impact materials	a. Bio materials b. Recyclable materials c. Clean materials d. Biodegradable materials e. Photodegradable materials	a. Renewable materials b. Biodegradable materials c. Compostable materials d. Clean materials e. Bio materials f. Photodegradable materials
2 – Reduction of material use	a. Biomimicry & bionics (biological structures) b. Reduction in weight c. Reduction in volume	a. Reduction in weight (less material = less pressure on biological life) b. Reduction in volume (transport)
3 – Optimisation of production techniques	a. Alternative production techniques b. Lower/cleaner energy consumption c. Less production waste d. Fewer/cleaner production consumables e. Industrial symbiosis	a. Alternative production techniques b. Lower/cleaner energy consumption c. Cultivation d. Fewer/cleaner production consumables
4 – Optimisation of Distribution System	a. Less/cleaner/reusable packaging b. Energy-efficient transport mode	a. Bio material packaging b. Energy-efficient transport mode c. Efficient distribution logistics – "grow it yourself" (e.g. mycelium - grow organism at home) d. Elimination of logistics – "do it yourself" (e.g. 3D print in house with starch-based polymers; cultivate material over structure in house; moulding bio waste materials etc.)
5 – Reduction of impact during use	a. Lower energy consumption b. Clean energy source c. Cleaner consumables	a. Clean energy source b. Clean consumables c. Fewer consumables needed d. No waste of energy/consumables
6 – Optimisation of initial lifetime	a. Biomimicry & bionics b. Dis- and reassembly c. Modular product structure (cell-like) d. Self-repair (e.g. self-sealing containers)	a. Reliability & durability (e.g. resistance to biodegradation before desired time) b. Easy maintenance & repair – e.g. self-repair & sustained growth (living materials)
7 – Optimisation of end-of-life system	a. Biodegradability b. Reuse of product c. Repurpose of product function	a. Biodegradability b. Compostable c. Solubility d. Nutritional value (waste=food) e. Compostability f. Photodegradation
@ – Development of new concepts / Product design review / Other design concepts	a. Biodegradability	a. Alternative (biological) production b. Shared cultivation of the material

The multiple loops approach herewith presented hypothesises that sustainable design can only be achieved if both biological and technical cycles are considered in equilibrium in the act of design (thinking, process and result). The strategies presented in Tables 1 and 2 are complementary; a comprehensive circular product design project will require utilisation of one or more of all four strategies.

5. Circular product strategy design cases

In order to illustrate the application of the four circular product design strategies, this section presents and analyses examples of product cases namely, i. Fairphone 2 (slow the loops), ii. Nike Considered Boot (close the loops); iii. C2C Coffee Cup (bio-based loops); iv. Mercedes-Benz Bionic Car (bio-inspired loops) (Figure 2). These examples have been chosen based on the relevant elements of their processes that stand out for each strategy, as illustrated in the loops diagrams (Figure 3).

5.1 Design to slow the loops – Fairphone 2

The Fairphone 2 represents a new approach to the design and manufacture of mobile phones. Founded in the Netherlands in 2013, Fairphone aims to “create positive social and environmental impact from the beginning to the end of a phone´s life cycle” (Fairphone, 2016) through four main principles: long lasting design, fair materials, good working conditions, and reuse and recycling.

The Fairphone 2’s relevant qualities to slow the loop focus on the later phases of its life cycle, emerging from its modular design (Table 3). Fairphone also emphasises its social responsibility in managing the end-of-life phase of both its and other brands’ mobile phones. Its partner, Teqcycle, receives used phones for refurbishment (for second-hand markets) and recycling (when refurbishment costs exceed phone value).

Table 3. Slow the loop Fairphone 2 LCD Analysis

Life Cycle Design Phase	Fairphone 2 Product Characteristics
Materials extraction - Selection of low impact materials	-preference for recycled materials and fair materials (including conflict free minerals & transparent sourcing)
Processing - Reduction of material use	NA
Manufacturing - Optimisation of production techniques	NA
Transportation - Optimisation of distribution	NA
Use - Reduction of impact during use	NA
Product life extension - Optimisation of lifetime	-‘long lasting design’ -modular design (easier maintenance & repair) -parts replaceable by users with basic tools -upgradability (advanced parts with additional functionality in development) -repair tutorials available on the Web -open source firmware (continuous updates by company & independent developers) -replaceable protective outer shell with rubber rim around glass (increased durability) -rigorous drop tests for survivability (from 1.85m on to concrete) -reuse programme (other brands also accepted)
End-of-life disposal - Optimisation of end-of-life system	-modular design (easy disassembly & refurbishment) -advanced ‘de-manufacturing’ processes for extraction of valuable materials from product for reuse (in development) -recycling programme (other brands also accepted)
New concept development	-social responsibility: -e-waste programme in Ghana, Africa (collection of discarded mobile phones to avoid bad waste management impact on the environment) -integration of social aspects of sustainability

Fairphone also aims to provide transparency in the management of the logistics of its raw materials, and the quality of the working conditions of its partners. However, no outstanding qualities stand out in the ‘processing’, ‘manufacturing’, ‘transportation’ and ‘use’ of their product, which leaves improvement opportunities for a complete circular product design implementation. For an illustration of the slow the loop strategy integration levels throughout the product life cycle phases, see Figure 3.

5.2 Design to close the loops – Nike Considered Boot

Nike Considered is a range of footwear by Nike Inc. The company claims to have sought to implement the best ideas of designers, both within and outside the company to ‘reinvent’ footwear, in response to consumer demand for more sustainable products (ecolabelindex, 2016; treehugger, 2005).

The Nike Considered boot focuses on considering the most appropriate materials throughout the whole life cycle of the product, with emphasis on the earlier and later phases (Table 4). The product also utilises mechanical construction where possible to decrease the amount of chemical adhesives in the product, gaining the added benefit of easier disassembly at the product’s end of life for recycling or refurbishing. The concept was Nike’s initial approach to close the loop and was further developed with Nike’s follow-up line ‘Flyknit’ (Nike, 2016). For an illustration of the close the loop strategy integration levels throughout the product life cycle phases, see Figure 3.

Table 4. Close the loop Nike Considered LCD Analysis

Life Cycle Design Phase	Nike Considered Product Characteristics
Materials extraction - Selection of low impact materials	-hemp & cotton for the fabrics and laces -recycled PET for lace tips -recycled factory waste rubber outsole (Nike Grind)
Processing - Reduction of material use	-minimising lining material -80% less solvent use -welt stitching on upper sole to minimise chemical adhesives -mechanical interlocking outer sole (no adhesives)
Manufacturing - Optimisation of production techniques	-’Vege-tan’ (vegetable dyed) leather body (cleaner production) -injection moulded Phylon midsole -mechanical interlocking outer sole (less energy)
Transportation - Optimisation of distribution	-close proximity material acquisition (within 320 km of Nike factory)
Use - Reduction of Impact during use	NA
Product life extension - Optimisation of lifetime	-Phylite (light & durable) sole -’Reuse-a-shoe’ take-back programme for refurbishment of unwanted/end-of-life products
End-of-life disposal - Optimisation of end-of-life system	-mechanical interlocking parts and general lack of adhesives, easier disassembly for recycling
New Concept Development	NA

5.3 Design for bio-based loops – C2C Coffee Cup

The C2C coffee cup is a concept by Saleem Khattak, never commercialised, that aimed to reduce waste from the disposable paper cups used in coffee chains throughout the world. The cup was intended to be manufactured on-site at cafes from the waste stream, using coffee grounds from previous customers and natural additives pressure-moulded to create the shape and form. The cup would have been fully biodegradable, with its final elements 100% compostable (Designboom, 2005).

The C2C coffee cup is a bio-based concept reusing (biological) coffee waste to construct a short-lived disposable product (Table 5). As opposed to the slow the loops example, this case illustrates a solution for biodegradable, low impact, fast consumption products. It also represents a form of industrial symbiosis on a micro level, reducing the use of consumables while utilising the waste stream as raw material for another industrial process. For an illustration of the bio-based loop strategy integration levels throughout the product life cycle phases, see Figure 3.

Table 5. Bio-based C2C Coffee Cup LCD Analysis

Life Cycle Design Phase	C2C Coffee Cup Product Characteristics
Materials extraction - Selection of low impact materials	-used coffee grounds (biological waste stream from coffee stores) (15%) -pulp filler & corn derived dextrose (polylactide) resin (85%)
Processing - Reduction of material use	NA
Manufacturing - Optimisation of production techniques	-in-house pressure moulding of material (low waste, low energy)
Transportation - Optimisation of distribution	-on-site utilisation of reuse/recycle/waste recovery system
Use - Reduction of impact during use	NA
Product life extension - Optimisation of lifetime	NA
End-of-life disposal - Optimisation of end-of-life system	-biological materials (compostable, biodegradable, photodegradable) -nutrition value of material for plants-insects
New concept development	-maintaining production machinery only in high-profile cafés can allow additional used coffee grounds to be brought in from others, raising coffee composition of cup to 90-95%

5.4 Design for Bio-inspired loops – Mercedes-Benz Bionic Car

The Mercedes-Benz Bionic Car was a concept developed by DaimlerChrysler, part of the Mercedes Group, in 1996. The vehicle drew structural and aesthetic inspiration from the yellow boxfish, a small, tropical coral reef fish, improving its aerodynamics and maintaining good structural integrity and large interior volume (mercedesclass.net, 2005).

The Mercedes-Benz Bionic Car concept focused on the engineering solutions presented by the physiology of the yellow boxfish, without direct consideration for sustainability (Table 6). However, this case represents a very good bio-inspired and high (energy) efficiency example, both in processing and use, as a direct result of the bionic interpretation of the boxfish's aerodynamic anatomy. Although the car remained on a concept prototype level, Mercedes claimed that elements of the vehicle would carry on to future design models.

For an illustration of the bio-inspired loop strategy integration levels throughout the product life cycle phases, with indicative data, see Figure 3.

Table 6. Bio-inspired Bionic Car LCD Analysis

Life Cycle Design Phase	Bionic Car Product Characteristics
Materials extraction - Selection of low impact materials	NA
Processing - Reduction of material use	-boxfish carapace inspired car frame allows reduction of materials while providing strength in necessary places
Manufacturing - Optimisation of production techniques	- Soft Kill Option (SKO) software for translation of biological structure to lightweight vehicle structure (bionics)
Transportation - Optimisation of distribution	-lightweight structure
Use - Reduction of impact during use	-bionic shape of vehicle reduces drag (0.19 C_d) for good speed (up to 190km/h) and efficient fuel consumption (2.9l/100km at 90km/h – 100mpg at 55mph) -lightweight structure -efficient oxidising catalytic converter & particulate filter allows efficiency of fuel consumption and cleaner emissions
Product life extension - Optimisation of lifetime	-bionic structure meets safety & durability standards for less material
End-of-life disposal - Optimisation of end-of-life system	NA
New concept development	-bionics & biomimicry as design principle

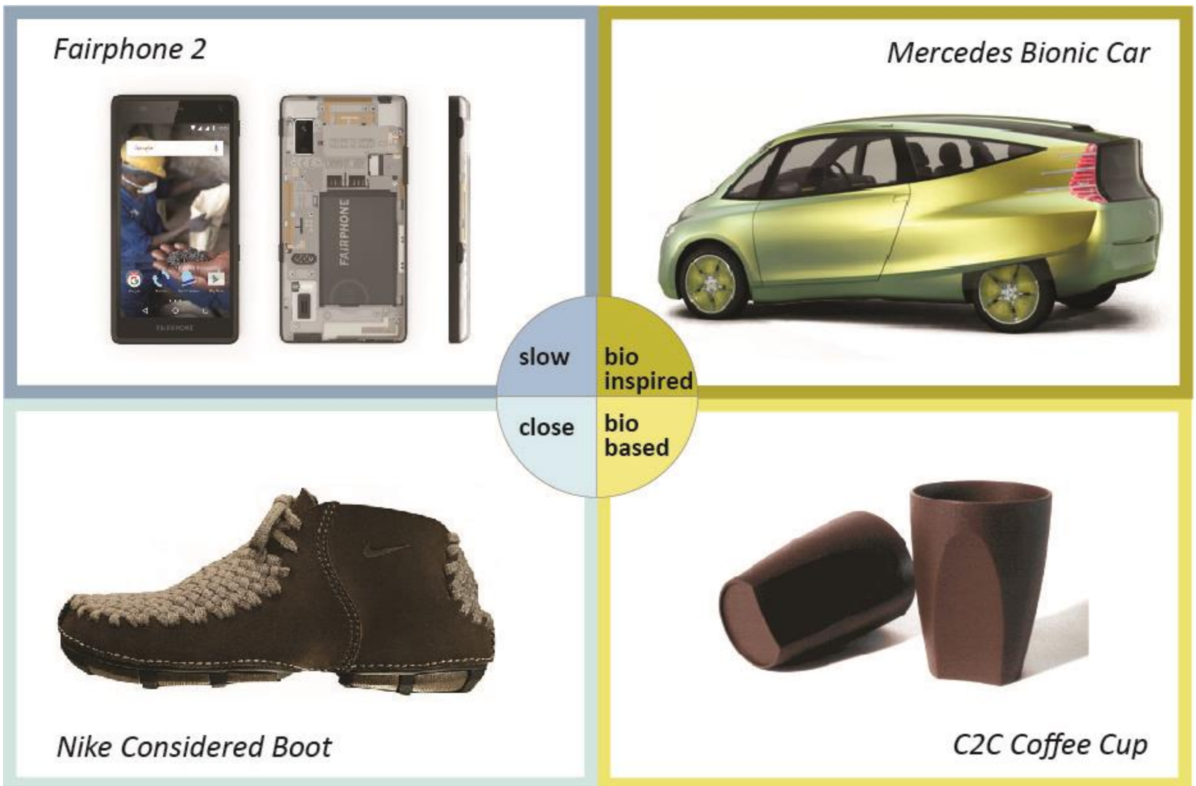

Figure 2. Four circular product design cases (Fairphone 2, Nike Considered Boot, Mercedes Bionic Car, C2C Coffee Cup)

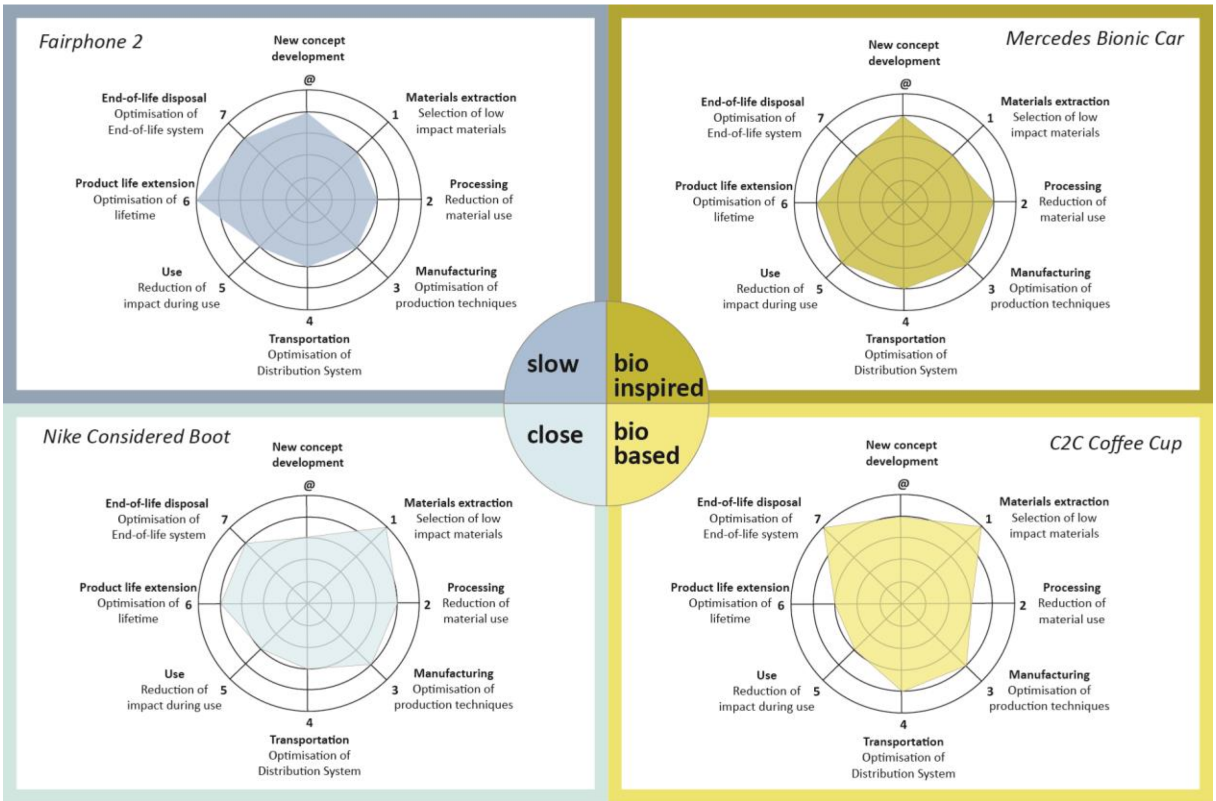

Figure 3. Multiple Loops Life Cycle Design Diagram (Fairphone 2, Nike Considered Boot, Mercedes Bionic Car, C2C Coffee Cup)

6. Conclusions and recommendations

In Europe's current socio-economic and political context, the Circular Economy vision is a potential contributor to increased design innovation, integrating a more systematic sustainability action plan into European companies, and consequently, their products.

While there is a positive vision and a set of policy measures to be operationalized, the priorities of the emerging circular economy framework in Europe need to be illustrated through novel business models and good design practices.

This paper is a methodological contribution to this area of study, presenting an approach to guide designers and product developers in the difficult process of creating effective and novel circular products, including the consideration of design strategies to lower the impacts of materials and energy use, processes and technologies in the whole life cycle of a product. Additionally, it aims to assist the process of tracking existing circular economy businesses and products by identifying best-case scenarios from which designers and industries can learn.

In analysing the four product cases, the study confirms that throughout the life cycle design phases there is no certainty in circular product design, in the sense of achieving a totally closed loop; however, short and medium term improvements and innovations may be achievable if a systematic plan for product design is taken into consideration within the Circular Economy vision.

While design for closing the loops is the logical vision in circularity, issues such as technical constraints, low user awareness and the conventional ownership culture, along with reluctance of many companies to maintain responsibility for the end of life of their products, impede the implementation of circular products in the market – especially in price competitive ones. Slow the loops and bio-loops (bio-based and bio-inspired) strategies aim to be complementary approaches.

The former may create a compromise between cost and socio-environmental responsibilities, notably by prolonging the use of products, while the latter ensures minimal waste generation at the end-of-life and full integration with the biological system (even though biodegradability by itself does not necessarily ensure zero waste or emissions). In this context, topics such as the management of the rate of biodegradation of materials are relevant future research areas in circular product design. Closing of material loops, however, should still be the ultimate vision of a circular product design process, one which integrates the slow the loops and bio loops strategies, and fosters new, efficient processes to increase product differentiation and add value. The promotion of cross-sectorial and inter-business cooperation is thus an important future action to undertake in the diffusion of circular product design, while promoting the search for future market opportunities and new business scenarios in the context of the circular economy.

In this context, governmental institutions and policy makers may consider the demand for a European circular entrepreneurial innovation system supported through the creation of incentives, with the establishment of government-funded demonstration projects for circular product design. At the same time, it is necessary to incorporate an academic approach to define the full range of options for circular product design, and to initiate a discussion about the role of design in higher education in this scenario.

Future research will refine the concepts and strategies presented in an operative model to test a detailed version of the Circular Product Design Multiple Loops Approach within the working environment of product designers. It will also consider a discussion to be initiated under a participatory approach, where policy makers, product developers, academics and researchers interact to identify best-case scenarios and solutions to be assessed, selected and disseminated.

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