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Proposal of a Dual Circularity Concept for Sustainable Design

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Abstract

Current CE approach, and its many definitions, does not explicitly consider the interconnectedness of the biological and technological cycle. This paper uses state-of-the-art to articulate nuances of the CE to encourage a more comprehensive understanding of the concept from a perspective of both cycles. The results address that acknowledged sustainably driven shifts of resources between cycles are neglected in most state-of-the-art. Therefore, the Dual Circularity (DC) definition is proposed and further evaluated by three examples.

Keywords: circular economy, sustainability, sustainable design, biologically inspired design

1. Introduction

Circular Economy (CE) has been widely recognised within academia, industry, organisations (Ellen MacArthur Foundation, 2013a) and policy-makers (European Commission, 2020) as a promising approach for achieving sustainable development and as an alternative to the current linear take-make-dispose system (EEA, 2020). European policy makers have introduced high-level CE strategies, and the business community plays a crucial role by taking up political ideas and applying new business models, and product design practices in moving our societies to CE (Geissdoerfer et al., 2017; Pieroni et al., 2020, 2021). The CE is based on various schools of thought, approaches and practices and it evolved differently in different cultural, social and political systems (Geissdoerfer et al., 2017; Winans et al., 2016). Due to various concepts, numerous definitions of CE exist, however, commonality found between most of them are the "value retention processes" or mechanisms to retain value through reuse, repair, refurbishment, remanufacturing, redistribution and recycling (Nasr et al., 2018; Schöggl et al., 2020). Moreover, the most popularized representation of CE system is that of distinguished technological and biological cycle (The Ellen MacArthur Foundation, 2015), a notion adopted from the Cradle-to-Cradle concept by (McDonough and Braungart, 2002). The concept separates biological resources, because of their regenerative nature (biological cycle) from abiotic or technical resources (technological cycle) (McDonough and Braungart, 2002). However, in practice, the distinction is not explicit, which therefore could lead to overlooking the potential contributions, such as improving circularity and environmental performance of resources (Harris et al., 2018). Many bio-based resources actually enter the technological cycle, for example, the use of wood and paper in many manufacturing applications (Berg et al., 2019; EEA, 2018). Furthermore, organic and inorganic elements are mixed and integrated in resources naturally (sedimentary rocks) or even designed in (car components) (Carus and Dammer, 2018; Velenturf et al., 2019). For instance, the European Commission and new CE action plan aim to promote bio-based, biodegradable and compostable plastic with an aim to improve environmental benefit and reduce use of fossil fuels (European Commission, 2020). Given the influence that the CE concept currently has, there is a clear risk of neglecting the benefits of using and recovering the value of resources at the end of the use, and therefore not achieving the full sustainability potential due to the lack of consideration of the dynamic links between the two cycles and their influence in the overall sustainability performance of the circular systems (Metic et al., 2021). Furthermore, choosing which loop to follow, and how to begin transitioning between one loop paradigm to another with perspective of both cycles could help companies to avoid loss of value of resources as long as possible (Metic et al., 2021).

To address this gap, in this paper, we propose a Dual Circularity (DC) approach, which advocates for having both biological and technological cycles in mind when deciding how products and systems are designed for a sustainability-driven shift to CE (Metic et al., 2021). In this context, the paper aims to identify main gaps in research considering available literature to propose DC definition. Next, to further develop argumentation on the current state of the art, analysis of examples based on the possibility of resources to circulate in and between cycles and loops are discussed.

2. Methodology

The key research questions guiding the research are: (1) How can DC help in a more comprehensive understanding of the CE concept? and (2) How can a DC approach support the design of more sustainable systems?

The methodology combines state-of-the-art review, the conceptualization of DC definition and preliminary testing of the approach using case exemplification, as following described. The main goal of the literature review was to provide a comprehensive understanding of the CE concept from a perspective of both technological and biological cycles. The focus of the analysis was to gain in-depth understanding of the research areas and their relationships with CE. The review concentrated on the evolution of the CE concept and findings of different research areas contributing to the formulation of the CE, complemented by available definitions and graphical representation. This was done by classifying and comparing findings to reflect gaps and problems and in order to draw argumentation for the conceptualization of the proposed DC approach. The approach towards the definition of DC was based on the literature review and supported through a number of well-defined criteria: (i) link to existing CE concepts, offering yet another understanding of the CE that contributes to the evolution of the CE concept; (ii) be helpful to decision-makers to select sustainable design options; (iii) create awareness of sustainability options in complex, dynamic systems. The definition was adjusted in an iterative approach that continuously allowed to integrate feedback from logical tests where the definition was applied to real-world scenarios. Furthermore, to evaluate the DC definition, three case examples were used. This enabled preliminary testing of the approach based on different segments of the definition, allowing for better clarity of thinking process and definition.

3. Results and analysis

3.1. Evolution of the concept and its definitions

The CE concept has been gaining momentum since 1970s, however, it became popularized in the 1990s as a response to economic growth and natural resource limitations (Winans et al., 2016). Evidence on the origin of the CE cannot be specifically traced (Ellen MacArthur Foundation, 2013a; Winans et al., 2016), since multiple contributors and approaches inspired the CE concept. The more contemporary understanding of CE has evolved by incorporating contributions from a variety of concepts and approaches that share a similar line of thought of closed loops (Geissdoerfer et al., 2017). The main contributions of the most represented concepts in the literature are presented in Table 1, with a focus on their views regarding the biological and technological cycles.

With such wide range of the different schools of thought, it is an imperative of having a lack of consensus on one definition of CE. Several academics already made extensive reviews on the definitions of CE considering wide range of topics (Geissdoerfer et al., 2017; Ghisellini et al., 2015; Homrich et al., 2017; Kirchherr et al., 2017; Murray et al., 2015; Prieto-Sandoval et al., 2017), as summarized in Table 2.

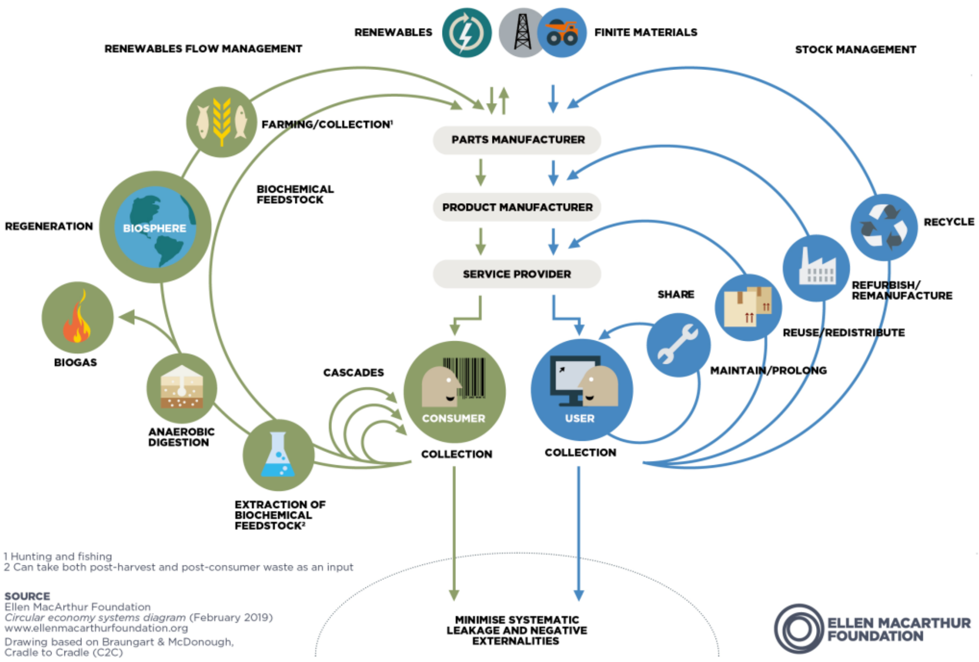
Table 1. Overview of the concepts contributing to the CE

Concept	Biological cycle	Technological cycle	Reference
Permaculture (Bill Mollison, David Holmgren - 1978)	A conscious design focused on maintenance of agro-ecological systems that mimic natural ecosystems in terms of variety, stability, and resilience - reproducing the no waste, closed-loop systems seen in different natural systems	N/A	(Homrich et al., 2017; Lewandowski, 2016)
Regenerative design (John Lyle, 1994)	Restorative design of socio-ecological systems within limits of available natural resources		(Geissdoerfer et al., 2017; Homrich et al., 2017)
Industrial ecology (Thomas E. Graedel, Braden R. Allenby - 1995)	Designing industrial systems in synchronization with environmental sustainability by forming closed-loop networks needing less inputs and producing less outputs (waste)		(Geissdoerfer et al., 2017; Homrich et al., 2017)
Cradle to Cradle (William McDonough, Michael Braungart - 2002)	Designing products that minimize negative impact while optimizing positive impact by viewing materials as nutrients circulating in closed-loop biological or technological cycles		(Geissdoerfer et al., 2017; Homrich et al., 2017; McDonough and Braungart, 2002)
Biomimicry (Janine Benyurs - 2002)	Designing nature-inspired solutions to design products, processes and systems		(Geissdoerfer et al., 2017; Homrich et al., 2017)
Performance Economy (Walther Stahel - 2010)	Strategies to maximize the value by favouring resource sufficiency over resource efficiency and creating competitiveness with a full shift to servitization		(Geissdoerfer et al., 2017; Homrich et al., 2017; Stahel, 2010)
Blue Economy (Gunter Pauli - 2010)	Principles for enhanced use of a blue resource, shifting from exploitation to the adoption of clean technologies		(Geissdoerfer et al., 2017; Homrich et al., 2017)

Table 2. Overview of the most commonly used definitions for Circular Economy (CE)

Reference	CE Definition	Cycle focus
(Ellen MacArthur Foundation, 2013a)	An industrial system is restorative or regenerative by intention and design-driven by four principles: (i) waste is equal food; meaning that restorative loops are the crucial idea, (ii) building resilience through variety, (iii) generating energy from renewable resources, and (iv) system thinking	**Biological** - the loops are regenerative - resources suitable for these processes are those that can be safely returned to nature
		Technological - the loops are restorative to maintain the value of products/materials at their highest at all times
(Murray et al., 2015)	An economy that does not affect the environment, rather it restores any impact done in resource attainment while ensuring little waste is produced through the production process and life cycle of the products.	**Biological** - ensuring the nature is being restored by any impact of resource extraction
		Technological - focus on waste minimization of products
(EC, 2015)	CE aims to maintain the value of resources for as long as possible by re-cycling them back into the product cycle at the end of their use while minimising waste generation.	**Biological** - N/A
		Technological - focus on maintaining value, recycling, minimising waste not explicitly mentioning biological aspects
(Geissdoerfer et al., 2017)	CE is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops, through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.	**Biological** - N/A
		Technological - focus on the loops within technological cycle not explicitly mentioning biological aspect

The concept of closing the system in terms of different loops is one of the most mentioned across different approaches contributing to CE. Moreover, the thinking is often incorporated with differentiating between the biological and technological aspects, as often presented with EMF diagram, Figure 1, (Ellen MacArthur Foundation, 2013b). Biological perspective is being more aligned with environmental and biological backgrounds in research, and technological aspect is more aligned with economic and industrial perspectives (Homrich et al., 2017; Metic et al., 2021). This gap or differentiation is obvious in the mentioned graphical representation of the EMF CE diagram. Nevertheless, in practice, the distinction between biological and technological aspects is not always clear: bio-based resources actually enter the technological cycle, at the same time as the use of bio-based resources is getting greater today as a potential sustainable shift from fossil-based materials (EEA, 2018; European Commission, 2020). The main focus is on systemic thinking, better use of resources and waste management with emphasis on economic and environmental benefit (Geissdoerfer et al., 2017).
Regarding the CE definitions, CE is defined as an economic system where end-of-life phase is replaced with one of the main principles (Kirchherr et al., 2017). The main principles recognized across the selected definitions suggest that resources can be designed to be cycled through the system as if they are in a nature, those include reuse, repair, refurbishment, remanufacturing, redistribution and recycling. And while some authors argue that the core idea of CE is to "mimic" biological processes through technological systems, most scholars still only focus on cascading and biodegradability of renewable materials in separate cycles (Geissdoerfer et al., 2017; Leipold and Petit-Boix, 2018; Murray *et al*., 2015).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 1. Circular Economy butterfly diagram (Ellen MacArthur Foundation, 2013a)

Table 3 shows what aspects are represented in the CE concept today by available definitions using examples and what aspects are not explicitly acknowledged. For example, by distinguishing two cycles, biological materials such as wood, cotton or bio-based products are always directed to end up in biological cycle, on the other hand, the technological origin materials and products (i.e. steel, fossil-based plastic and minerals), as well as products of mixed materials, are always directed towards technological cycle. In doing so, represented concepts tend to overlook the contribution, such as improving circularity and environmental performance, that reuse, refurbishment, remanufacturing and recycling of renewable materials can have (Harris et al., 2018). Moreover, some materials of the technological origin could be as well directed to the biological cycle at the end of life (EoL) to reduce waste and landfilling especially when recycling is not an option. Further, there is a big need to have viable options for different materials when they are mixed in a product for better managing at the EoL.

Table 3. Material/product origin and their end-of-life cycle representation in the CE

		MATERIAL/PRODUCT ORIGIN		
		BIOLOGICAL	TECHNOLOGICAL	MIX
END OF LIFE CYCLE	BIOLOGICAL	BIO-BASED PLASTIC WOOD COTTON		
	TECHNOLOGICAL		STEEL FOSSIL-BASED PLASTIC MINERALS	FURNITURE FABRICS ELECTRONICS PACKAGING

3.2. Conceptualizing the Dual Circularity approach

Based on the above state-of-the-art review, this paper proposes the definition of the Dual Circularity concept, which strives to recognize biological and technological cycles while simultaneously considering materials and products to switch between cycles. In this context, Dual Circularity is defined as:

"A holistic approach to support decision making when designing a CE initiative which fully considers the flow of materials/products within and between biological and technological cycles targeted at the enhanced overall sustainability performance of the system."

To detail the definition, the following sub-sections elaborate on the definition's main elements.

3.2.1. Holistic approach

The main aim of DC is to contribute to the focus of CE, closing the resource loops for as long as possible while maintaining the highest value of materials and products by highlighting the interconnections of both biological and technological cycles from a sustainability perspective. In that way, the main principles (or R strategies), as defined by Kirchherr et al. (2017), are extended to the option of returning a substance to the biosphere. In contrast to existing approaches, the understanding of circularity in a DC is not limited to materials flowing in two distinct cycles but considers the possibility of materials switching cycles. A detailed explanation is provided in sub-section 3.2.3.

3.2.2. Decision support when designing a CE initiative

The design phase is a window of opportunity where the designer has comparably great leverage to influence the sustainability performance of products (Pigosso et al., 2014). In the design phase, important decisions are made which determine later EoL options of products and consequently impact a material's or product's overall sustainability performance (Rodrigues et al., 2017). The DC approach strives to create awareness to spot possible opportunities to extract value by combinations of loops and cycles that products and materials can flow in. In that way, a product or material's properties can be customized early to facilitate sustainable material and product flows. Taking advantage of early sustainability choices helps to facilitate a quick and effective shift of the current economy towards a less linear and more sustainable circular economy.

3.2.3. Material/Products flow in and between biological and technological cycle

In a DC approach, materials and products flow through cycles and loops, which can be switched. Hereby, as in CE approach, the loops are EoL strategies that are applied to materials or products (e.g. reuse, remanufacture, etc.), while cycles refer to biological and technological realms in which materials and products flow. So far, technological and biological cycles are defined by the material flowing in them (see e.g. EMF's definition in section 3.1). This means, a material's origin may be in one cycle, while its EoL takes place in the other cycle (an example are drop-in plastics, like bio-PET, made from biological material but not biodegradable). Consequently, an additional category besides biological and technological material is needed: dual material. A dual material is a material, which has its origin in another cycle than its EoL. The definition of biological and technological cycles in a DC, therefore, is: (i) a biological cycle is a cycle in which biological and/or dual material flows; (ii) a technological cycle is a cycle in which technological, and/or dual material flows. Widening the view to the product perspective, a product can consist of a multitude of materials, including biological, technological, and dual materials. The goal of DC is still the same as in the CE approach: to keep products for as long as possible in loops to preserve the highest possible value (in the order share/maintain/prolong, reuse/redistribute, refurbish/remanufacture, recycle). Only in the last resort, products are disassembled in their components to allow for recycling. Products made from materials of different categories should therefore remain in loops of the technological cycle for as long as possible. After no other loop option than recycling is left, the product will be disassembled and flow through the cycles that are optimal for the respective material. For a product that contains biological and technological materials, this could mean, for example, that parts of the product keep flowing in the technological cycle, while other parts are transferred to the biological cycle. Building on this idea, another distinction can be made between cycles: primary and secondary cycles. A primary cycle includes all loops that preserve a product or material's value for as long as possible, while a product's properties and/or purpose are most widely retained. On the other hand, a secondary cycle contains the loop in which a product is disassembled in its components to allow for individual treatment of materials in biological or technological cycles. For example, a wooden wristwatch is in its primary cycle as long as it is continuously reused, repaired, refurbished, etc. When there is no other option but recycling left, the wristwatch will enter the secondary cycle. Here, the watch is disassembled to obtain separate materials. Metal components, for instance, can be recycled in the technological cycle while wooden parts of the watch could be returned to the biosphere and thus enter the biological cycle.

3.2.4. Enhancing the overall system sustainability performance

The Dual Circularity concept recognizes that economic activities of any sort are embedded in a complex system whose elements interact in an action-reaction scheme over time. An example is economic activities that emit substances, which contribute to global warming. Changes in the climate system, in turn, may affect economic activities. Causal links cannot always be intuitionally grasped but require a methodological system analysis. The DC concept strives to provide a basis for system analysis approaches that are capable of anticipating systemic effects and identifying sustainable alternatives from a systems-thinking point of view.

3.3. Case Exemplification

To exemplify the gap in the research and to test the proposed DC definition, case examples based on the material origin and EoL cycle options are further explored and discussed. The purpose is to identify whether there are any logical ambiguities or contradictions when the perspectives of a biological and a technological cycle are applied to real-world scenarios. In addition, the test aims to check whether the definitions are useful for decision-makers. The examples of materials/products switching between cycles show that the interconnectedness of technological and biological cycles, as defined in this paper, allow the analysis of products/materials to switch cycles with addressing every possible benefit.

3.3.1. Example 1 - Green Fibre Bottle

The Green Fibre Bottle resulted from an innovation project carried out by EcoX-Pac and Carlsberg, in collaboration with the Technical University of Denmark (Carlsberg Group, 2019). The bottle is made from sustainably sourced fibres and it is intended to be a fully biodegradable wood fibre beverage bottle and an alternative to existing glass and plastic bottles (Didone et al., 2017). The purpose is to help achieve the transition to a sustainable circular economy and to ensure fail-safe disposal if a bottle ends up in nature (Carlsberg Group, 2015). The green fibre bottle complements the DC approach and definition, in a sense that even though the origin of the product is biological, the primary end of the cycle is not necessarily biological (Table 3). To retain most of the materials' value for as long as possible, the primary option for an EoL cycle should be technological R loop strategies (i.e. recycling), with a focus on keeping value of the paper-based material. When material recycling is no longer possible, or when the product is not disposed of properly (e.g. due to consumer behaviour), the product can always be safely transferred to the biological cycle (secondary cycle). Moreover, the market for green fibre bottle packaging is expected to expand with other market giants such as L'Oréal and Coca-Cola which have recently become partners in the initiative (Carlsberg Group, 2019).

Table 4. Example of green fibre bottle

	Description
Example	**Green fibre bottle**
Material Origin	**Biological**
Holistic approach	Green fibre bottle due to origin as well as design has the potential to shift between the technological and the biological cycle
Decision support	The bottle is designed to be looped several times and circulated between cycles, which contributes to making a decision when selecting which loop to follow in a way that a product's value is maintained at the highest level at all times.
Shift of products/materials between cycles	The product is of a biological origin, and designed to ensure a fail-safe disposal if littered in nature. However, it is intended to enter the current waste management system for recycling, which sets the primary choice of the cycle to be technological. Only when recycling is no longer a possibility, the bottle is planned to be biodegraded, setting this as a secondary choice of cycle.
Enhancing the overall system performance	The design of the bottle has the potential to contribute to a more sustainable performance of the CE system in a way of switching cycles as it is possible to retain its value for longer.

3.3.2. Example 2 - Fossil based compostable plastic packaging

Plastic pollution is an increasing problem, not just on land but in the water bodies as well (EC, 2015). Therefore, plastic is being included as one of the five priorities of the EC action plan for CE, which aims to increase the rate of recycled plastic to 55% and reduce landfilling to less than 10% by 2030 (EC, 2015). Besides their light weight, durability and flexibility, plastic packaging and bags have a short life-time which results in increasing waste generation and demands proper EoL management (Geyer et al., 2017; Hahladakis and Iacovidou, 2018). However, only a small percentage (20%) of plastic packaging is being recycled on a global level (European Commission, 2020). Some fossil fuel-based (FB) plastics are recyclable and some are biodegradable in certain environments (Hann et al., 2020). Which again reflects another possibility not addressed in CE diagram. Fossil-based compostable plastics can fully or partly be made from fossil fuels, those include: PBAT (polybutylene adipate-co-terephthalate), PBS (polybutylene succinate), PCL (polycaprolactone) and PVA (polyvinyl alcohol) (Hann et al., 2020). Therefore, even though some of the packaging and bags are of a technological origin (i.e. based on fossil fuel), they can have both a technological and/or a biological EoL cycle (Table 4). Due to higher value retention, the primary cycle choice should, in most cases, be technological. However, the potential sustainability performance of the biological cycle as secondary choice should also be explored. Considering the biological cycles when deciding which cycle to follow in certain stage, can help reduce landfilling, and emission from incineration. Contributing to better overall performance of the system. In this context, there are certain limitations as confusion with consumer and manufactures not being able to distinguish between different types of plastic due to origin and EoL possibilities. This is again, where DC can help by specifically addressing the types of plastic able to be cycled in technological and biological cycle.

Table 5. Example of fossil-based compostable plastic

	Description
Example	**Fossil based compostable plastic packaging**
Material Origin	**Technological**
Holistic approach	Some FB plastics due to their origin have the potential to shift between the technological and the biological cycle.
Decision support	FB plastic can be designed into products such as packaging to be looped several times and circulated between cycles, which contributes to making a decision when selecting which loop to follow in a way that a product's value is maintained at the highest level at all times.
Shift of products/materials between cycles	For FB plastic, the primary choice of the cycle is technological. Furthermore, it eventually can be either recycled or if nothing else is possible returned to nature, setting this as a secondary choice of cycle
Enhancing the overall system performance	The use of FB plastic in a product has the potential to contribute to a more sustainable performance of the CE system in this way it is possible to retain its value for longer

3.3.3. Example 3 - Tetra Pak mixed materials

Tetra Pak or aseptic beverage cartons are multi-material, paper-based packaging, produced by laminating layers of paper, low-density polyethene and aluminium foil (Zawadiak, 2017). Material recycling for this packaging type is fairly complicated due to multiple types of materials bonded together (Robertson, 2021). In the EU, the recycling rate of Tetra Pak is around 40%, and the recycled material is usually used in other applications not requiring virgin material properties (e.g. construction material) (Robertson, 2021). Incineration with energy recovery is also a common EoL strategy (Robertson, 2021; Zawadiak, 2017). Robertson (2021) provided a review of a number of recycling options and technologies for aseptic beverage cartons (Robertson, 2021). The fact is that the utility of Tetra Pak is lower than from other pure paper packaging when considering benefits of CE initiatives such as recycling, furthermore, there are challenges for economically processing aluminium as well as collecting and sorting the cartons (European Commission, 2020; Robertson, 2021). The DC approach can be helpful to decide what will be the most beneficial option for this product, (Table 5). Again, the primary focus is to keep the products/materials in, between the cycles, and as long as possible circulating. The choice will again depend on the types of materials in the products and their quality. Due to multiple materials, certain limitations arise, as mentioned; these are connected to the level of value, economical perspective, availability of technologies. For the paper share of the material, if it is not profitable and/or possible to have it on acceptable level in technical cycle it can be returned to biological cycle. While plastic and aluminium can be recycled or cascaded, until possible in the technical cycle. In this way, paper can be further used in paper products instead of virgin materials, and a similar approach can be applied for the aluminium and metal-based resources.

Table 6. Example of mixed materials Tetra Pak

	Description
Example	**Tetra Pak**
Material Origin	**Technological**
Holistic approach	Tetra Pak due to its mixed origin have the potential to shift between technological and biological cycle
Decision support	Tetra Pak due to its multi-material design is able to be looped several times and circulated between cycles, which contributes to making a decision when selecting which loop to follow in a way that products value is maintained at the highest level at all time
Shift of products/materials between cycles	For Tetra Pak, due to mixed material, the primary choice of the cycle will usually depend on the type of material and its quality. Furthermore, again the goal is for material to stay in the cycle that can retain its value for as long as possible. However, for materials for example of biological origins such as paper, or fossil-based compostable plastic they could as well be safely returned to the nature
Enhancing the overall system performance	The use of Tetra Pak has the potential to contribute to a more sustainable performance of the CE system in this way that it is possible to retain its value for longer period

4. Discussion

Despite the surge in the existing literature, there is still a need to establish a better understanding of the CE concept, particularly in relation to the interrelationships between the biological and technological cycles, as defined by the CE butterfly diagram (Figure 1). In reality, technological and biological materials are mixed or used instead of one another (i.e. bio-based materials instead of fossil-based) - reflecting the possibility of shifting the cycles as well as being able to circulate less or more within a certain cycle. Moreover, the CE concept does not exclude nor explicitly include the perspective of both cycles in design thinking. Therefore, to better grasp the CE concept and ensure better understanding, a DC approach is proposed and discussed in this paper.

Furthermore, a number of case examples are used to test the DC definition, which helps to sharpen the understanding of DC. Ultimately, how far an alternative is sustainable depends on the product context (e.g. raw material origins, production procedures, applications, etc.). Therefore, by our analysis, DC is a good approach to highlight opportunities resources when considering EoL management.

Nevertheless, there are constraints to DC. First, as with other CE definitions, DC is conceptualized with a special focus in mind. In this context, DC tries to highlight that materials and products can switch cycles. Thereby, not all elemental aspects of a CE may be captured. This is because the definition is formulated to be generally applicable and holistic. This attempt comes at the cost of special-case considerations.

Second, DC can support decision making by providing a wide base of alternatives to choose from (e.g. instead of choosing between products that flow in the biological cycle or products that flow in the technological cycle a decision-maker could decide for a product that flows in both cycles). However, DC cannot state which alternative is the most sustainable one. To do so, sustainability assessment approaches are necessary (e.g. Life Cycle Sustainability Assessments (LCSA), carbon footprints, techno-economic assessments, etc.).

Lastly, DC tries to be one further step in the development of CE definitions. At the same time, the field develops fast. This brings new aspects and challenges to a CE definition and will ultimately require a further advancement of existing concepts, including the DC approach.

5. Conclusion

The contribution of the DC approach is three-fold; firstly, the understanding of CE is expanded by discussing and analysing the evolution of the concept and its definitions. Secondly, a DC approach is proposed, which emphasizes the significance of including and explicitly referring to both biological and technological cycles, which promotes material resilience, extends possibilities of closing, narrowing and slowing the loops. Thirdly, examples are used to further develop the argumentation and preliminary test DC approach definition.

The results presented in this paper provide the foundation for the development of a framework that can enable dual circularity modelling of industrial and societal products from a sustainability perspective. The framework will ultimately support decision-makers and designers with guidelines to aid the considerations of which circularity loops and cycles to choose and how to design the transition between cycles and loops. Moreover, the framework will enable identifying and mitigating possible trade-offs and rebound effects emerging from designing for DC.

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