Product-level circularity metrics based on the “Closing–Slowing Future–Past” quadrant model

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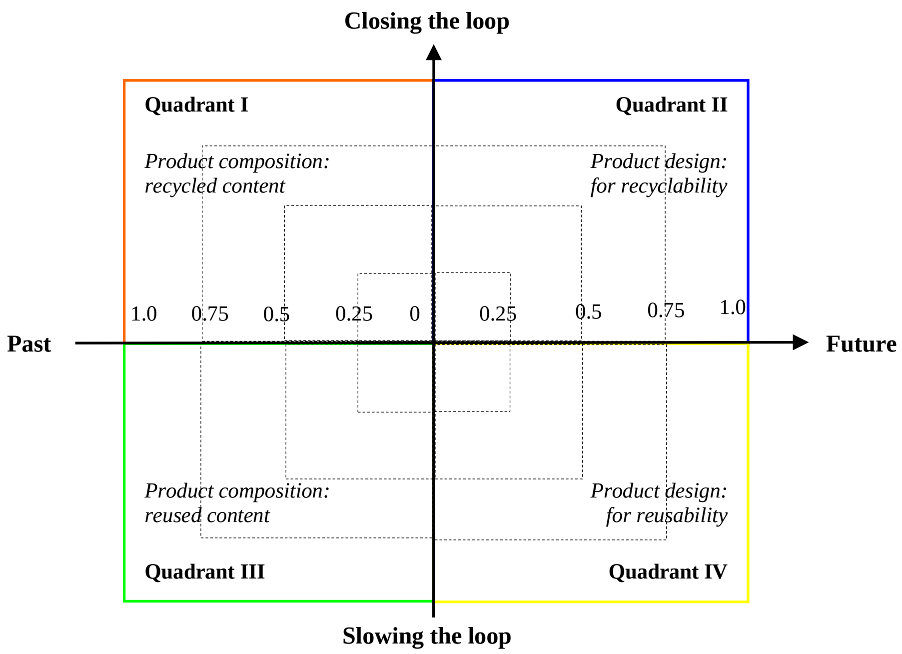
Abstract

Critical literature review coupled with conceptual analysis provides a holistic framework for measuring a product's circularity performance based on its integrated contribution to the operationalization of various configurations of circular economy (CE) strategies. The following main results were obtained. First, we outline the "Closing–Slowing and Future–Past" ("CSFP") quadrant model ("CSFP" quadrant model) of CE-related product attributes and the circular product categories derived as findings of our previous study in the form of modifications to develop a product-level circularity metric. Second, we propose fifteen product circularity profiles with singular and configurative CE strategy-related contributions building on the "CSFP" model and circular product categories. Third, we quantify the 6Rs (reuse, repair, refurbishment, remanufacturing, repurposing, recycling) for the strategy-related contributions derived from the "CSFP" quadrant model to propose a product circularity data profile coupled with a metrical scale for measuring product circularity performance and visualizing quantified circular contributions. To trial, showcase and validate the relevance of the developed model and associated visualization tool, we conduct two case studies comparing the circularity performances of smartphones and packaging bags, respectively. Companies can use the proposed framework as a maturity scale to enhance the circularity performance of a product. This work contributes to a more accurate measurement of product circularity performance and a sharper understanding of its integrated contribution to circular strategies.

Keywords: Circular economy, Product circularity, Circularity performance, Circularity indicator, Circularity metrics, Circular product categorization.

Graphical abstract



1. Introduction

The circular economy (CE) represents the most recent attempt to conceptualize the integration of economic activity and environmental wellbeing in a sustainable way (Murray et al., 2015), and is often considered an umbrella concept encompassing different meanings (Moraga et al., 2019). To assess the progress and effectiveness of actions in terms of stepping towards a CE, it is crucial to have a reliable set of indicators, which demands the development of circularity metrics for evaluating CE performance. To support this effort, CE operationalization consists in translating 6R circular strategies (Modak, 2021) or extended 10Rs (Morseletto, 2020) from concepts into parameters, then searching for ways to fix the object parameters, substantiate these parameters, and finally direct the fixing of data available for observation and measurement (Shevchenko and Danko, 2021). Note that existing practices for measuring this progress fail to fully reflect such concepts as the lifecycles of a material and product which are measured by the number of turns and duration of each turn. In addition, metrics need to be developed to answer the question of how fully the available circularity potential is used for implementing circular strategies at a given company. It is equally important to know the progress made in building up and transforming a new circularity potential that has no resources today but offers future opportunities to reduce the number of undesirable outputs in the economic system in general. However, the absence of adequate unified metrics and standards has been a key barrier to the integration of resource efficiency requirements (Tecchio et al., 2017; Boyer et al., 2021).

The starting point for any circularity metric is a unit of measure. To quantify circularity, available metrics build on various types of units, typically mass (Haas et al., 2015), number of processes (Bailey et al., 2008), material turnover frequency (Figge et al., 2018), or longevity (Franklin-Johnson et al., 2016), etc. Measurement scales can use both physical indicators (Haas et al., 2015) and cost indicators (Di Maio et al., 2017; Linder et al., 2017). A circularity measurement tool can build on a single synthetic indicator (EMF and Granta, 2017) or a set of indicators (Elia et al., 2016). Circularity can be measured at any level, from individual firm to inter-firm and macro-level (EASAC, 2016).

In terms of salient research themes, CE measurement-related papers over the past decade have focused on (i) material flow analysis (MFA) as a tool to monitor progress toward CE (Wang et al., 2020; Islam et al., 2019; Mayer et al., 2019), (ii) lifecycle assessment (LCA) as an approach to assess environmental benefit (Niero and Kalbar, 2019; Adibi et al., 2017), (iii) articulating circularity with sustainability and sustainable development (Kravchenko et al., 2019; Padilla-Rivera et al., 2021), and (iv) industrial ecology and resource efficiency (Domenech et al., 2019; Fraccascia et al., 2021; Wang et al., 2021). To address the issue of saving material resource value and preventing environmental pollution to achieve sustainable circularity, attempts have been made to combine methods, e.g. material circularity indicator (MCI) and LCA (Glogic et al. 2021; Lonca et al. 2018; Niero and Kalbar, 2019), product-level circularity and LCA (Linder et al., 2020), LCA and LCC (Fregonara et al. 2017), and even LCA, MFA and lifecycle costing (LCC) (Cobo et al. 2019). Furthermore, the growing visibility of CE and cascading use of material resources have increased the need to coherently address multifunctional issues for modeling multiple lifecycles in LCA (Tanguay et al., 2021; Schulte et al., 2021). Despite significant efforts of the scholarship to develop methods, approaches, techniques, prototypes, and tools for measuring circularity, the debate on which metrics are best suited for CE is still unresolved.

The product-level metrics side of CE operationalization is still an under-researched area. Niero and Kalbar (2019) assert that no consensus has yet been reached on what product-level CE indicators should measure, which creates a subjective methodological framework for assessing CE strategies. Recent scholarship features several solid studies focusing on product-level measurement approaches and metric tools for assessing circularity, in particular the works of Jerome et al. (2022) on mapping and testing CE product-level indicators and Saidani et al. (2017) on requirements for the design of a circularity measurement framework to assess product performance. A comprehensive review of the extant literature on product-level metrics, presented in Section 3.1 in more detail, covers approaches and tools, with a focus on various units (Maio et al., 2017; Figge et al., 2018; Linder et al., 2017) and circular strategies (Vanegas et al., 2018; Razza et al., 2020; Bracquené et al., 2020) or their configurations (Boyer et al., 2021; Mesa et al., 2018).

In light of the studies on the product-level measurement, the present analysis finds that while the circularity metrics emphasize the various indicators in terms of level, focus, and units, which may contribute to finer-grained assessment, they also carry limitations – a lack of a *single* circularity metric accompanied by appropriate product-level data for use as a convenient tool by all actors in the value chain. In addition, our review reveals that there is no *quick-and-easy tool* at the product level for quantification and visualization of the integrated circular contribution of *various configurations* of circular strategies. A quick-and-easy tool would have a clear purpose and easy manageability, and at the same time, the accuracy needed to make it a valuable technique for real-world application by any stakeholder, i.e. (i) developers in product design or redesign, to augment the degree of circularity of a product, (ii) business leaders, to build up the circularity potential of a product produced by them, (iii) policy-makers, to develop policies to support the growth of products with the highest circular impact within a particular product group, (iv) practitioners, to search for new ways to increase circularity, and (v) consumers, who need to be made aware of the circular impact of a specific product.

Therefore, this study addresses the following research question: How can we determine a product circularity performance in a quick-and-easy and transparent manner for use as a metric by any stakeholder within a circular product system, including the consumer?

Our study starts with (i) a discussion of existing product-level metrics and (ii) a clarification of all possible features, properties, and characteristics inherent to products generated by pro-circular businesses. Then, to show the background of this study, we present a modified version of the "Closing–Slowing and Future–Past" quadrant model ("CSFP" model) and an enhanced version of the five-level inverted pyramid for ranking the fifteen circular product categories based on our previous study (Shevchenko et al., 2022). Moving forward, we build on the "CSFP" quadrant model to (i) develop the fifteen product circularity profiles and also (ii) propose a product circularity data profile coupled with a metrical scale as an accurate measurement tool based on the quantification of 6R strategy-related contributions. The findings contribute to the subject area by proposing a novel framework for measuring product circularity performance based on its consolidated contribution to the operationalization of various configurations of circular strategies derived from the previously-developed circular product categorization scheme.

The remainder of the paper is organized as follows. *Section 2* clarifies the research methodology applied. *Section 3* presents the research background for this study regarding product measurement and classification according to their circularity. *Section 4* presents the inclusive framework for measuring product circularity performance. The findings of this research are discussed in *Section 5*. *Section 6* concludes the paper and outlines the main research contributions.

2. Methods

This study employed a two-stage method combining critical review and conceptual analysis. In this regard, in order to develop an inclusive framework for measuring the circularity performance of a product based on its integrated contribution to the operationalization of various configurations of circular strategies, a critical review adopted from Ranjbari et al. (2018) based on the PRISMA framework (Page et al., 2021) was carried out to overview the extant literature and establish a baseline for product-level circularity metrics and classifications of products contributing to the CE.

Employing a well-structured research protocol plays a significant role in the soundness of the data collection process, and accordingly catching the most relevant articles from the target domain (Ranjbari et al., 2022). On this basis, taking the three main keywords of the current study (i.e., "circular economy", "product", and "indicator") into account, different combinations of these keywords were tested to design an effective search string. As a result, the following search string was designed to explore articles within the Scopus database: (search in article title: "circular economy" OR "closed-loop economy" OR "circularity" OR "circular business") AND (search in article title, abstract, keywords: "product") AND (search in article title: "typology" OR "framework" OR "categorization" OR "classification" OR "taxonomy" OR "indicator*" OR "metric*" OR "measure*" OR "index" OR "matrix" OR "scale" OR "assess*" OR "evaluat*" OR "quantif*"). Scopus was selected as the main database of this research due to its wide coverage of peer-reviewed documents providing an inclusive overview of the global research output in academia (Chàfer et al., 2020).

To ensure sufficient coverage of the literature, no time limit was considered to extract articles published in this area. The initial run of the search string returned a total of 339 documents. Non-English materials were excluded from the data, resulting in removing 7 documents from the sample. In the next step, the results were limited to only peer-reviewed articles published in journals and other types of publications, such as conference proceedings and book chapters were excluded to enhance the quality of the data collected. Consequently, 263 peer-reviewed journal articles remained for further consideration in the next step. The remaining articles were carefully screened to remove the papers that are not relevant to the main focus of the current study. As a result, a total of 69 peer-reviewed English-language articles remained to build the final sample for further analysis in this research as illustrated in **Fig. 1**. In this regard, a conceptual analysis adopted from Hicks (2020) was performed on the selected articles to effectively analyze and synthesize the existing product circularity metrics and indicators for developing a generic product ranking framework based on the assessment of their integrated contribution to the operationalization of circular strategies.

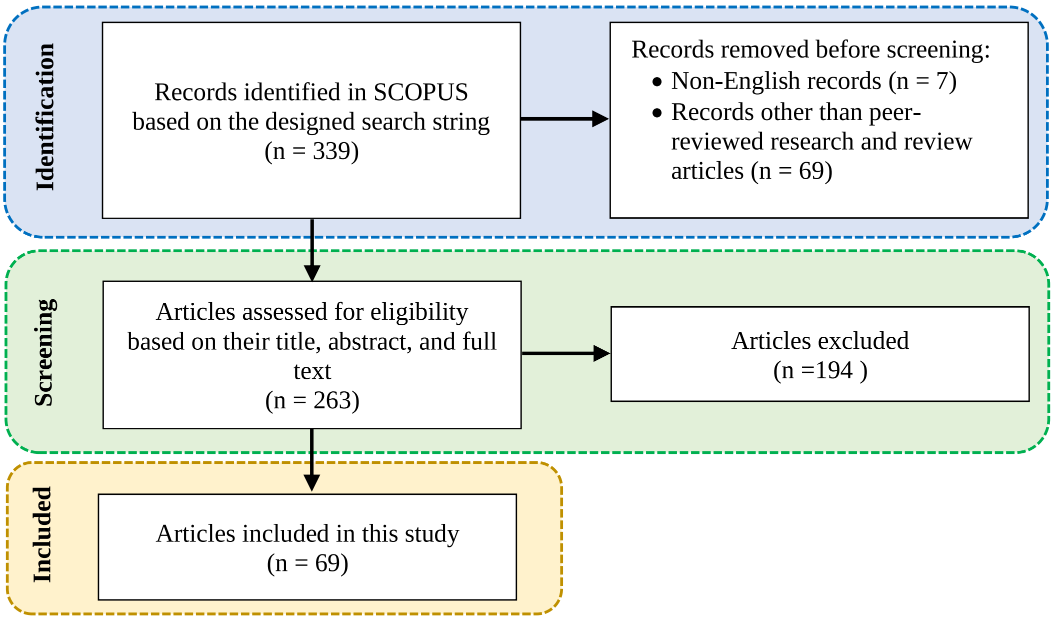


Fig. 1 Data collection process based on the PRISMA framework

3. Literature review

3.1 Product-level circularity metrics under discussion in the scholarship

Measuring and assessing circularity performances are not yet a common practice in organizations (Sassanelli et al., 2019). Nevertheless, different metric tools have been presented and various approaches to deal with the circularity assessment have been adopted in the literature. According to Boyer et al. (2021), measuring product-level circularity should consider ways to achieve high material recirculation, high utilization, and high endurance in products and service offerings. This should be considered in the early stages of product design and development, as circularity decisions made at this stage play a significant role in the circularity and sustainability performance of a product over its lifecycle (Kamp Albæk et al., 2020). In this regard, Mesa et al. (2020) developed a single generic indicator based on durability and environmental footprint for material selection as an early step in the design process towards the extension of product lifespan. The issue of ease of product disassembly to support CE strategies was considered by Vanegas et al. (2018), who believed that reducing disassembly time and the related costs would increase the economic feasibility of product lifetime extension and therefore increase the viability of a CE at a regional level. In order to measure a product's circularity, Linder et al. (2017) developed a product circularity metric indicator based on the use of the economic value for aggregating recirculated and non-recirculated elements of a product into a combined measure of product circularity, whereas Mesa et al. (2018) developed a new product family approach to measuring the circularity of product families based on six indicators related to material flow, reusability, reconfiguration, and functional performance. Di Maio et al. (2017) proposed a value-based indicator for simultaneous measurement of resource efficiency and CE in terms of the market value of "stressed" resources, and Navare et al. (2021) investigated the circularity metrics of technical and biological cycles. Razza et al. (2020) led a similar to the latter study where a methodological approach for calculating the circularity of biobased and biodegradable products was developed and applied to biodegradable mulch films. Bracquené et al. (2020) developed a product circularity indicator taking into account the tightness of the material cycles and their relationship with other product systems, such as the use or supply of recycled materials. Franklin-Johnson et al. (2016) asserted that circularity can be assessed by the longevity indicator, as it reflects the period during which a resource provides value. However, Figge et al. (2018) argued that material circularity is not necessarily an indicator of longevity, as a material can be used multiple times but within a short period.

This overview of circularity indicators shows that most indicators at the nano and micro levels (i.e. materials and products, respectively) are in the developing stage and that their main focus is on recycling and reuse rather than other dimensions such as energy, emissions, and water, whereas innovative technical solutions such as design for adaptability and disassembly have already been widely applied to measure the circular potential of structures (Khadim et al., 2022). There is also a widely-spread confusion and overlap between indicators for circular processes and indicators on circular impacts (Garcia-Saravia et al., 2022). However, considering the lack of consensus on product-level CE indicators and the requisite methodological framework, Niero and Kalbar (2019) showed that coupling material circularity indicators with lifecycle-based indicators via multi-criteria decision-making analysis can help deal with conflicting situations where the selection of the best alternative may be biased by the metric chosen. To indicate possible characteristics of indicators for measuring the performance of products within the EMF CE, Cayzer et al. (2017) proposed a prototype of CE indicators, based on feedback from CE experts, with a single aggregated metric for each lifecycle stage. As the authors highlighted, this approach has several advantages, such as ease of use, simplicity, speed, and an effective metaphor for the diffusion of CE principles, but it also carries limitations, namely the opaque and potentially misleading nature of a single metric, superficial engagement with decision-making, and reliance on context-specific assumptions (Cayzer et al., 2017).

In addition to measurement approaches and metrics for assessing circularity, the literature also proposes frameworks and classifications of indicators. Kristensen and Mosgaard (2020) assert that there is still no widely-accepted framework for measuring CE in general at the micro-level or within circular strategies. Saidani et al. (2019) identified 55 sets of circularity indicators focusing on different purposes, scopes, and potential applications. Their study proposed a taxonomy of circularity indicators introducing 10 categories of indicators. Garza-Reyes et al. (2019) developed a conceptual circularity measurement toolkit to assess the degree of circularity in manufacturing SMEs and define the different types of circular initiatives mobilized. Parchomenko et al. (2019) employed the Multiple Correspondence Analysis method to assess 63 circularity metrics and 24 CE-related features with a focus on recycling efficiency, longevity, and stock availability. Elia et al. (2016) developed a four-pillar framework for measuring progress towards the CE that includes the processes to be observed, the activities involved, the parameters to be measured, and the levels of implementation of circular strategies. A framework to categorize indicators based on circular strategies and measurement scope was proposed by Moraga et al. (2019) to clarify what the indicators are measuring, and which embraces different types of strategies grouped according to how they preserve functions, products, components, materials, or embodied energy. Kristensen and Mosgaard (2020) conducted a similar study to provide a categorization of existing micro-level indicators in which the majority of the 30 selected CE-related micro-level indicators focus on recycling, end-of-life management, or remanufacturing, while the other indicators consider disassembly, lifetime extension, waste management, resource efficiency, or reuse. While Pollard et al. (2022) developed, rated, and validated micro-level circularity indicators relevant to electrical and electronic sector products, Superti et al. (2021) highlighted 57 CE indicators in urban areas and categorized them based on three conceptual frameworks of the STEEP categories, Sustainable Development Goals, and inductively-created thematic groups. To clarify what actually has to be assessed and how, Vinante et al. (2021) summarized insights from 130 papers on existing CE metrics and mapped them according to a new circular value-chain framework. As a result of such mapping, 365 different firm-level related metrics were identified and classified through this framework and converted into 23 categories. To provide a complete overview of CE indexes, De Pascale et al. (2021) analyzed 61 indicators and further grouped them according to the three spatial dimensions of sustainability, i.e., macro, meso, and micro, also based on the core 3R CE principles. The findings, in the form of information related to the formulation strategy, scaling, normalization, weighting, and aggregation methodology, enable readers to get a dedicated toolkit (De Pascale et al., 2021).

In order to assess the circularity levels and overcome the barriers to implementing CE practices, CE maturity models and matrices are being developed by the CE research community. Uhrenholt et al. (2022) adopted a resource-based view and presented a maturity model to support organizations in their CE transformation with assessment tools. A product design maturity matrix was proposed by Aguiar and Jugend (2022), which contained five maturity levels corresponding to the evolutionary plateau that allows the diagnosis of the strengths and weaknesses of the circular product design process, and eleven dimensions of analysis regarding the product design strategies and the managerial aspects of the circular product design within the design process. The majority of research conducted on the design for circularity has been focused on theoretical and conceptual implications rather than practical implications (Dokter et al., 2021). The focus of the design process for the CE is shifting from a singular object to the creation of systems, business models, and collaborative networks (Dokter et al., 2021). Besides, Sumter et al. (2021) provided nine key competencies for design in a CE to support design practice and guide the design development methods in circular design, including "(1) circular systems thinking, (2) design for recovery, (3) design for multiple use cycles, (4) circular business propositions, (5) circular user engagement, (6) circular materials and manufacturing (7) circular impact assessment, (8) circular economy collaboration, and (9) circular economy Storytelling".

The present analysis finds that while the circularity metrics emphasize the various indicators in terms of level, focus, and units, which can help produce a finer-grained, they also carry limitations in that they lack a single product-level circularity metric, accompanied by appropriate data, to afford a simple, clear and concise tool for shared use by all actors in the value chain and all the possible stakeholders—including consumers—involved in a circular product system for saving the value of materials and products for as long as possible. Note too that existing methodological approaches and tools for the assessment of product circularity have a number of weaknesses primarily related to the fact that they tend to focus on only one strategy, employ a lot of parameters, mobilize complicated algorithms, need long computation times, and measure the result of our decisions in the past without considering the future circularity potential.

The significant role of circular product design has gained momentum among CE practitioners, researchers, and policy-makers. This is mainly due to the fact that closing the loop and CE business models are functional only if the products and services are designed for circularity (Shahbazi and Jönbrink, 2020). However, the gradual incorporation of CE tools, methods, and practices within new product development processes is still in its infancy stage (Aguiar and Jugend, 2022). Although the expected value from the CE in theory is indispensable, product take-back systems are often in pilot or small scales and are facing some major challenges and obstacles to becoming financially viable and widely adopted within manufacturing systems (Uhrenholt et al., 2022). In this vein, in a structured literature review, Uhrenholt et al. (2022) highlighted context, supply chain, and company as the main three factors affecting the financial performance of product take-back systems in a circular economy. Franco (2019), through the development of a System Dynamics model, showed a systemic effect of combining a business model and multiple product design strategies on transitioning towards a circular economy and closing resource loops. Dahmani et al. (2021) proposed combining lean design with Industry 4.0 and eco-design as an innovative model to enhance the sustainability of the product lifecycle through reducing costs and environmental impacts, enhancing product design, and improving efficiency in businesses. Moreno et al. (2016), through developing a comprehensive conceptual framework for circular design, proposed a set of 10 points to be considered when designing for a CE, including (1) design for "systems change" when considering any circular design strategy, (2) design by identifying the new circular business model that the product is being designed for, (3) design by thinking of revolutionizing the world, (4) design for multiple cycles and not only with EoL in mind, (5) design by thinking in living and adaptive systems, (6) design with various participants in the value chain, including end users, (7) design by considering value in a wider lens, not as a price tag on a shop shelf, but as an asset, (8) design with failure in mind, (9) design knowing where each material and part comes from and goes to, and (10) design with "hands-on" experiences that encourage a call for action.

In order to operationalize the CE model, it is necessary to translate the circular strategy-related concepts into a set of reliable constructors. The main issue that needs to be addressed here is what principal concepts or attributes across these all circular strategies inherent to the product do we really need to quantify? In an effort to gain a systematic understanding of the key attributes of a circular product, the next section tries to find out what properties, features, characteristics, and attributes underpin a pro-CE product in the context of circular strategies.

3.2 CE-oriented product attributes model

The circular strategy hierarchy derived from the "butterfly diagram" proposed by the Ellen MacArthur Foundation (EMF) (EMF 2014) is the most recent advance in the conceptualization of the CE model. According to the definition presented in the EMF's first report, a CE is an industrial system that is restorative or regenerative by intention and design. In addition to this, it shifts towards the exploitation of renewable energy, eliminates the use of toxic chemicals which hampers reuse and aims to eliminate waste through superior materials, products, systems, and business model design (EMF, 2013). Circular business model design is about saving the value of materials and products in the economic system for as long as possible (Bakker et al., 2014; Hofmann et al., 2017), which translates into a number of circular strategies. The actual number is still disputed: Modak (2021) proposed 6Rs circular strategies and Morseletto (2020) proposed 10Rs strategies. In this study, we will adhere to the list of 6Rs circular strategies that prioritize "reuse", "repair", "refurbishment", "remanufacturing", "repurposing", and "recycling", as it reflects the essence of the EMF definition.

In line with these strategies, there are a number of characteristics and attributes that distinguish a CE-related product from a linear economy (LE) related product. In general, a circular product generated by a circular business differs from a linear one in that it contributes to the implementation of *at least one* of the circular strategies listed above, even if this contribution is only of *slightly significant* importance. Along these lines, if we assume that design for recyclability saves only half of the materials contained in the product, then it means that a recycling strategy can be realized in the future for the part of materials that have circularity potential. The residual materials are essentially the *unavailable circularity potential* for the product but can become *available circularity potential* due to the *superior* design of the product. If there is no "circular" contribution in terms of circular strategies operationalization, then the product can rightly be classified as "linear". This viewpoint is in line with Kane et al. (2018) that define a CE in terms of material flows and consider the elimination of waste as the aim of a CE.

The reasoning behind loop-closing and loop-slowing strategies being central conceptual points of the CE (Stahel, 2010), the objects of operationalization are the "value of a material" and the "value of a product". In one of the leading schools of thought on the concept of CE, the performance economy championed by W. Stahel describes the economic system in terms of material loops and distinguishes two ways of avoiding wastage within technogenic cycles, namely recycling and reuse. He emphasized the axiom of the smallest loop as the most profitable, thereby highlighting the importance of product restoration through repair, modernization, and reuse of parts and modules of complex products (Stahel 2014). Stahel's idea of closing and slowing loops was widely accepted in the scholarship around the operationalization of circular strategies either for product recycling or product life extension through maintenance, repair, reuse, remanufacturing, and refurbishing (Bakker et al., 2014; EMF, 2014). All CE strategies can therefore fall into two principal directions, namely loop-closing strategies or loop-slowing strategies, which makes it possible to situate the "circular" contribution of the object of operationalization.

To build up product circularity potential in terms of moving towards avoiding wastage today and in the future, it is crucial to provide superior product design. To address this challenge, Hollander et al. (2017) proposed the guiding principles, design strategies, and methods required for circular product design, which plays a vital role in this regard. They developed a typology of approaches underpinning Design for Product Integrity, with a focus on tangible durable consumer products for a deeper understanding of the role of product design in a CE. This typology includes three main blocks: (i) long use design for physical and emotional durability, (ii) extended use design for maintenance and upgrading, and (iii) design for recontextualizing, repair, refurbishment, and remanufacture (Hollander et al. 2017). A further focal point of circular product design is to design for recycling or recyclability. Design for recyclability is also actively discussed in academic circles in terms of closing the loop across various materials, particularly within the packaging industry (Eriksen and Astrup, 2019), electronics industry (Atlason et al., 2017; Schaik and Reuter, 2010), textile and clothing industry (Laitala et l., 2015), and automotive industry (Ferrao and Amaral, 2006).

Note that product design for recycling is directly concerned with material circularity or closing the loop, and can be considered an integral part of product circularity in terms of appropriate design – product design for recyclability. Slowing-the-loop strategies increase product circularity to product design for reusability. Hence, in terms of the product-level circular design, the principal characteristics of the product in terms of saving the value of materials and products in the future are *design for reusability* and *recyclability*. At the same time, circular product design is also about saving the value of materials and products today to avoid waste generated in the past, i.e. the use of recycled materials and modules/parts obtained from end-of-life (EoL) products with design for reusability and recyclability. Hence, the principal characteristics of a product in terms of saving the value in the past also include *the presence of reused and recycled contents in product composition*. Eventually, following two types of CE loop contributions, we propose to consider such CE-related product attributes as (i) products that contribute to closing the loop – recyclable products and products with recycled content, and (ii) products that contribute to slowing the loop – reusable products and products with reused content.

According to Bocken et al. (2017), discussion about product circularity inevitably leads to a discussion of the circularity of the materials that these products are made of. Braungart et al. (2007) worked on the notion of the link between material circularity and product circularity to capture and increase circularity potential, with a focus on materials. The authors argued that ‘circularity potential’ should be considered in the context of multiple uses of materials. They asserted that a synthetic or mineral material can be determined as a technical ingredient if it has the potential to stay within the system of manufacturing, regeneration, and reuse to maintain the highest value through *product lifecycles*. This assertion highlights that material circularity works from a long-term perspective. By contrast, the product/modules/parts restoration paradigm looks at preserving value in a short-term period. Hence, from the long-term perspective, a slowing-the-loop product attribute will have less priority than a closing-the-loop attribute and should thus prevail in the event of design conflicts. This makes it vital to combine circular strategies in order to maximize the length of the useful life of both the product and the materials embodied in the product. Findings from scholarship on product and material circularity potential include underlying categories (EMF 2013a; Shevchenko et al. 2021), basal properties (Park and Chertow 2014), structural elements of circularity potential (EMF 2013b), and approaches for quantifying circularity potential (Eriksen et al. 2019; Vadenbo et al. 2016).

Blomsma and Brennan (2017) highlighted the need to shift away from implementing and assessing singular strategies and towards efforts to assess different circular configurations when several strategies can be made to work together. We assume that such configuration options can be operationalized (i) in series or (ii) in parallel. For instance, "product with reused and recycled contents" leads to circular strategies in parallel, and "recyclable product with reused content" leads to circular strategies in series.

This analysis takes us to the conclusion that if a product has the potential for implementing several strategies simultaneously, then it has quite a high circular impact. Moreover, if product design integrates the attributes of closing and slowing the loop in the past and the future simultaneously, then it will have the highest circular impact. In this vein, based on the essence of the categories slowing and closing the loops (Stahel 2010; Bakker et al., 2014) and the priority lent to circular strategies (Stahel 2014) with a particular focus on the product design framework toward a CE adopted from Hollander et al. (2017), a CE-oriented product attributes model for characterizing circular products is presented in **Fig. 2** as the modified version from Shevchenko et al. (2022).

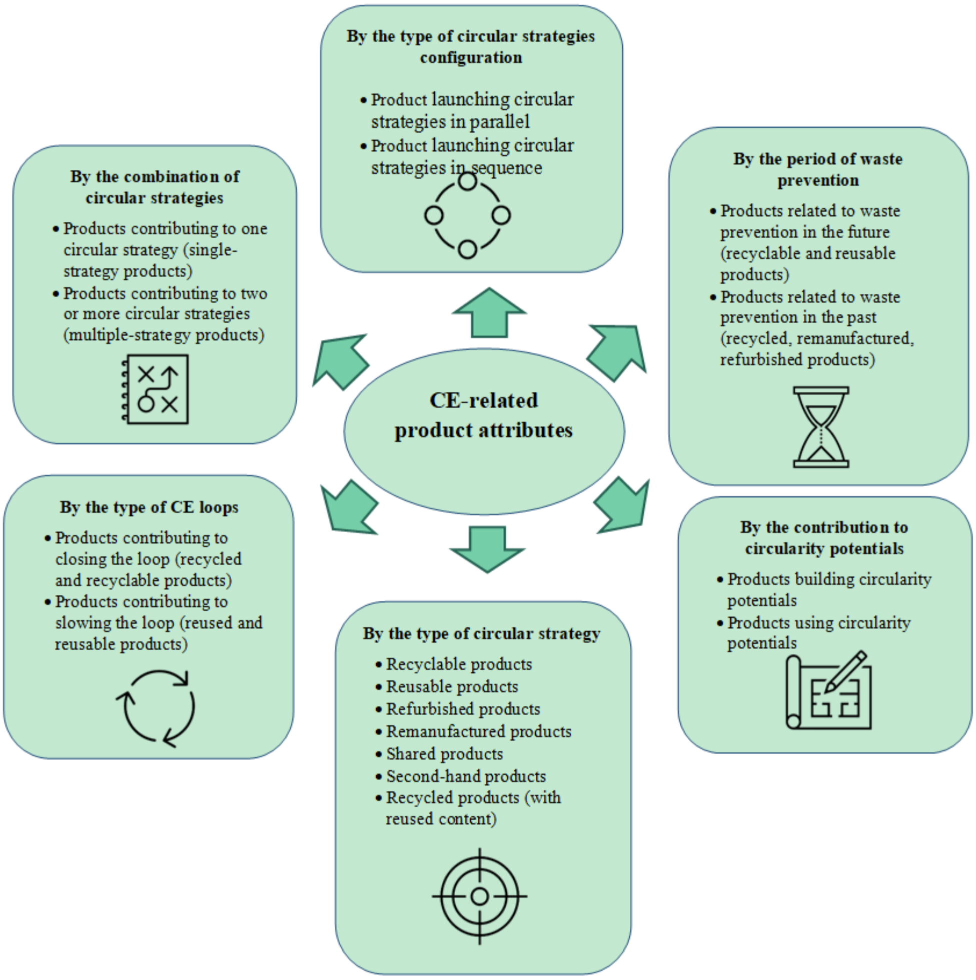


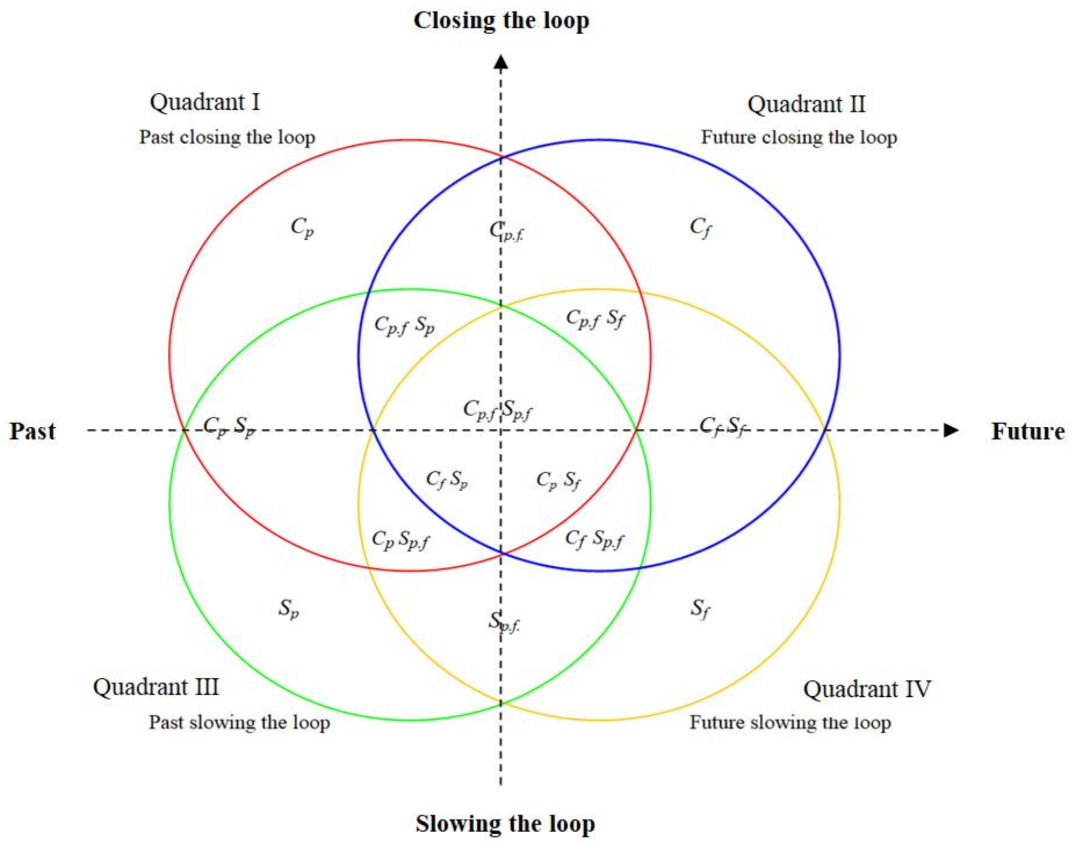
Fig. 2 CE-related product attributes model (modified version, adopted from Shevchenko et al., 2022)

To measure the singular and configurative CE strategies-related contributions at the product level, we consider it essential to build upon the unified circular products categorization scheme based on all possible combinations of the principal circular product attributes.

4. Results

4.1 'Closing–Slowing Future–Past' quadrant and the resulting 15 circular product categories

According to our previous study (Shevchenko et al., 2022), if we combine two essential attributes of CE-oriented products, in particular (i) type of CE loops (closing and slowing) and (ii) period of waste prevention (past and future), then four combinations emerge. A "Closing–Slowing Future–Past" quadrant model ("CSFP" quadrant) is presented as a modified version in **Fig. 3** illustrating these combinations.



Notation:

S_p – past slowing loop-based products; C_p – past closing loop-based products; $C_p\ S_p$ – past closing and slowing loop-based products; S_f – future slowing loop-based products; S_{pf} – future and past slowing loop-based products; $C_p\ S_f$ – future slowing and past closing loop-based products; $C_p\ S_{pf}$ – future slowing and past closing and slowing loop-based products; C_f – future closing loop-based products; $C_f\ S_f$ – future closing and slowing loop-based products; $C_f\ S_p$ – future closing and past slowing loop-based products; C_{pf} – future and past closing loop-based products; $C_{pf}\ S_p$ – future closing and past closing and slowing loop-based products; $C_f\ S_{pf}$ – future closing and slowing and past slowing loop-based products; $C_{pf}\ S_f$ – future closing and slowing and past closing loop-based products; $C_{pf}\ S_{pf}$ – future and past closing and slowing loop-based products.

Fig. 3 "Closing–Slowing Future–Past" quadrant of CE-related products
(modified version from Shevchenko et al. 2022)

The CSFP quadrant model includes the following quadrants: Quadrant I – past closing the loop (product with recycled content); Quadrant II – future closing the loop (recyclable product); Quadrant III – future slowing the loop (reusable product); Quadrant IV – past slowing the loop (product with reused content). **Fig. 3** also illustrates fifteen circular product categories that result from all possible combinations of product attributes mentioned below.

Table 1 presents the description of circular product categories in terms of circular strategies coverage with an interpretation of the types of strategy configurations. Characteristics of products are given under each category.

Table 1. Circular product categories interpreted in terms of circular strategies' contribution

Circular product category	Circular strategy contribution	Type of strategy configuration	Product description
1. Past slowing loop-based products (S_p)	Single strategy	–	Products with reused content
2. Past closing loop-based products (C_p)	Single strategy	–	Products with recycled content
3. Past closing and slowing loop-based products (C_p S_p)	Strategy configuration	In parallel today	Products with reused and recycled content
4. Future slowing loop-based products (S_f)	Single strategy	–	Reusable (upgradable, reparable) products
5. Future and past slowing loop-based products (S_{pf})	Single strategy	–	Reusable products with reused content
6. Future slowing and past closing loop-based products (C_p S_f)	Strategy configuration	In sequence	Reusable products with recycled content
7. Future slowing and past closing and slowing loop-based products (C_p S_{pf})	Strategy configuration	In sequence and additionally in parallel today	Reusable products with recycled and reused content
8. Future closing loop-based products (C_f)	Single strategy	–	Recyclable products
9. Future closing and slowing loop-based products (C_f S_f)	Strategy configuration	In parallel in the future	Reusable and recyclable products
10. Future closing and past slowing loop-based products (C_f S_p)	Strategy configuration	In sequence	Recyclable products with reused content
11. Future and past closing loop-based products (C_{pf})	Single strategy	–	Recyclable products with recycled content
12. Future closing and past closing and slowing loop-based products (C_{pf} S_p)	Strategy configuration	In sequence and additionally in parallel today	Recyclable products with reused and recycled content
13. Future closing and slowing and past slowing loop-based products (C_f S_{pf})	Strategy configuration	In sequence and additionally in parallel in the future	Recyclable and reusable products with reused content
14. Future closing and slowing and past closing loop-based products (C_{pf} S_f)	Strategy configuration	In sequence and additionally in parallel in the future	Recyclable and reusable products with recycled content
15. Future and past closing and slowing loop-based products (C_{pf} S_{pf})	Strategy configuration	In sequence and additionally in parallel today and in the future	Recyclable and reusable products with recycled and reused content

(i) Single strategy operationalization

As can be seen from Table 1, the "past closing loop-based product" (C_p) category covers all possible products with reused content. The products of this category contribute to the CE by closing the loop for some materials in the past but only allowing to operationalize one circular strategy, namely saving the value of materials. The "future closing loop-based product" (C_f) category embraces all possible products that are fully or partly recyclable. The products under this category contribute to the CE by waste prevention in the future and, therefore, building up material circularity potential for future use. Recyclable products belong to a single circular strategy as they only contribute to closing the loop. Likewise, the "future slowing loop-based product" (S_f) category comprises all possible reusable products that refer to a single strategy with a contribution to slowing the loop.

(ii) Strategy configuration operationalization

As shown in Table 1, the "future closing and slowing loop-based product" ($C_f S_f$) category embraces a set of products having such attributes as reusability and recyclability simultaneously. As the products of this category simultaneously contribute to slowing and closing the loop in the future, they can serve to operationalize several strategies *in parallel in the future*. In contrast, the "past closing and slowing loop-based products" ($C_p S_p$) category covers all possible products with recycled and reused content where several strategies are working *in parallel today.*

The "future closing and past slowing loop-based products" ($C_f S_p$) category comprises all possible recyclable products produced using reused content. As the products of this category simultaneously contribute to slowing the loop in the future and closing the loop in the past, they can serve to operationalize several strategies *in sequence*. The "future closing and slowing and past slowing loop-based products" ($C_f S_{pf}$) category covers all possible products having such attributes as reusability and recyclability simultaneously and also produced using reused content. As the products of this category simultaneously contribute to slowing the loop in the past and closing and slowing the loop in the future, they can serve to operationalize strategy configurations *in sequence and additionally in parallel in the future*. Finally, the "future and past closing and slowing loop-based products" ($C_{pf} S_{pf}$) category embraces products with design for reusable and recyclable and also have reused and recycled content in the composition. Such products operationalize several strategies *in sequence and additionally in parallel today and in the future.*

4.2 Five-level inverted pyramid for ranking the fifteen circular product categories

Fig. 4 presents a five-level inverted pyramid for the classification of the fifteen categories of CE-related products as a modified version based on our previous study (Shevchenko et al., 2022). It shows that there is a wide range of product contributions to the CE with a positive trend from linear to circular systems dealing with various levels of circularity. On this basis, the more linear a system is, the less it will contribute to the CE, whereas the more circular a system is, the more it will contribute to the CE. Accumulating waste and creating waste-related issues for future generations (see the top triangle in **Fig. 4**) is thus a negative contribution of the products to the CE that will lead to the creation of more linear systems rather than more circular systems. The highest level of linearity with strong adverse effects on product contribution to the CE concerns the generation if toxic waste exposing future generations to environmental risks.

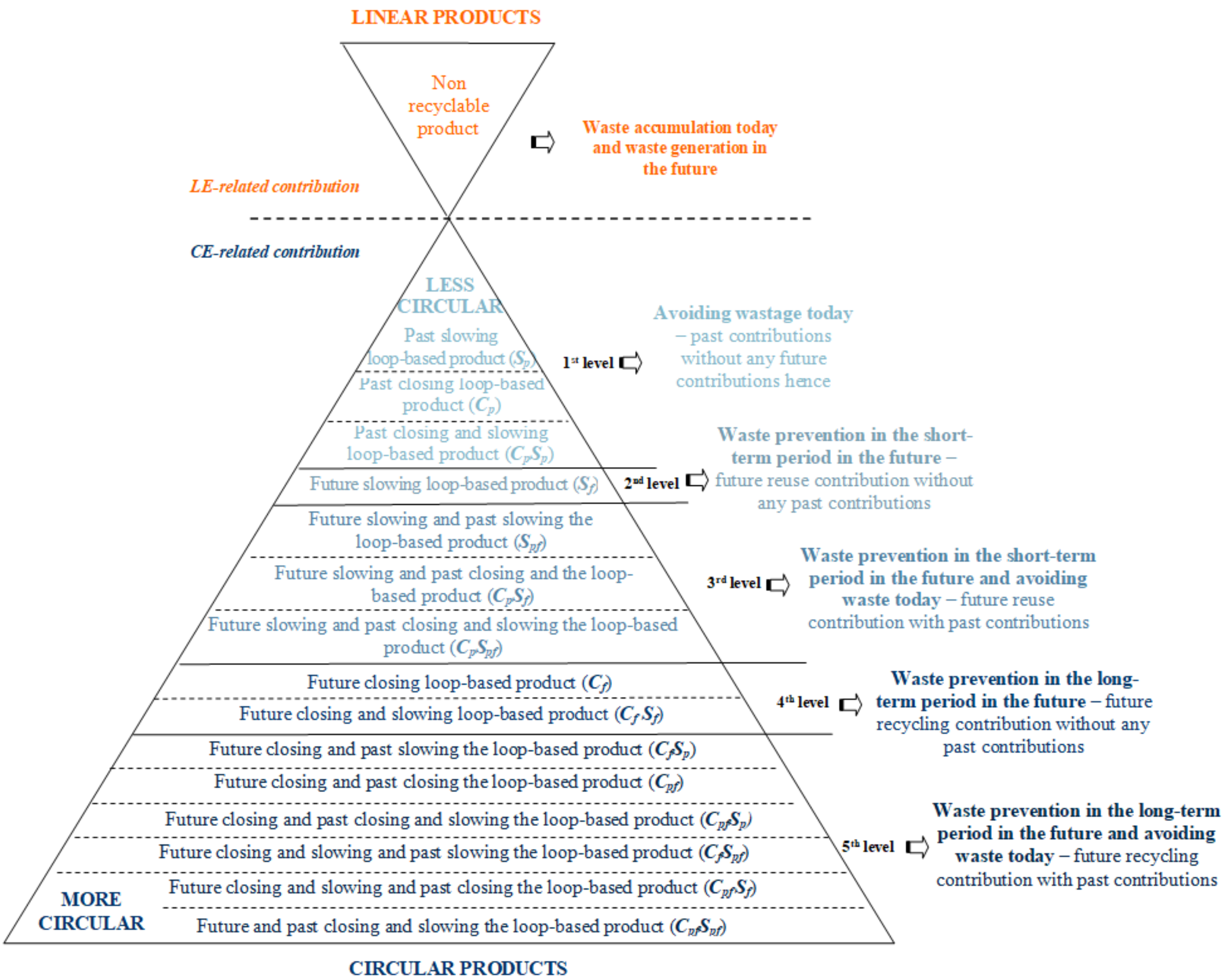
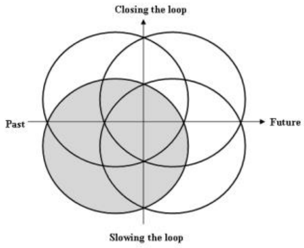
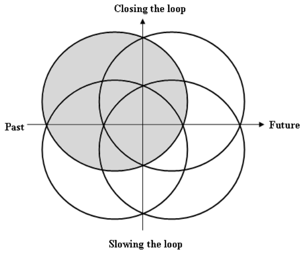
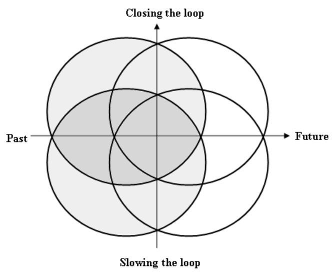
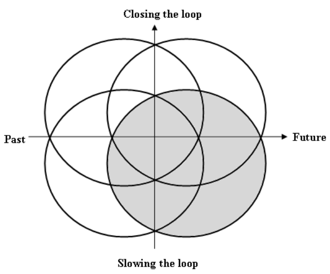
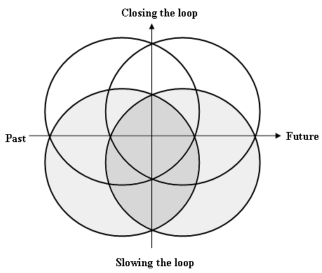
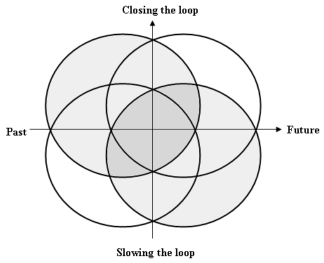
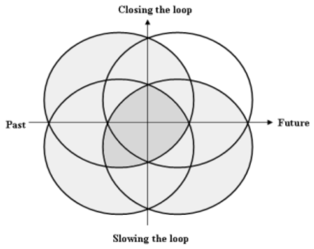
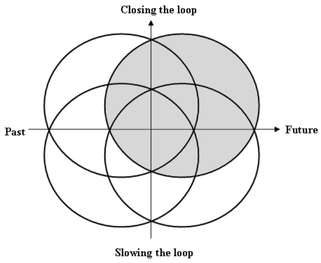
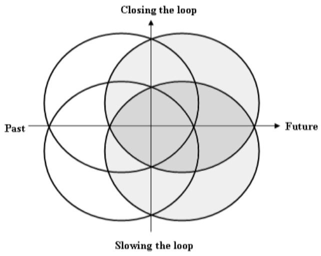
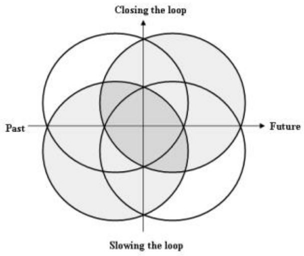
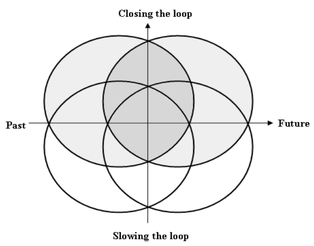


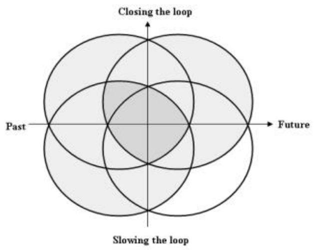
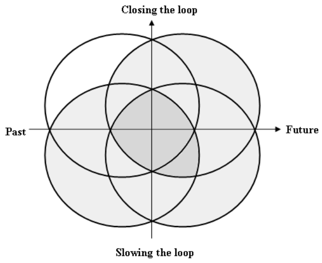
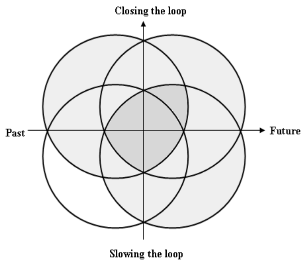
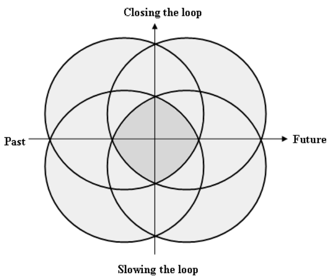
Fig. 4 A five-level inverted pyramid for the classification of fifteen categories of CE-related products (augmented version, inspired from Shevchenko et al. 2022)

The pyramid dealing with the CE-related contributions has five levels of product circularity, from less circular up to more circular. Table 2 presents the description of fifteen categories by the level of contribution of product circularity and circular impact, and also provides product circularity profiles to visualize their circular strategy-related contributions. This relatively generic description of the categories allows us to measure the circularity of products within any industry, and to subsequently assess the available circularity potential for these products and the unused potential.

Table 2 Description of the categories of CE-related products by level of contribution

Circular product category	Product circularity profile	Level of product circularity contribution	Circular product impact	Description of the circular product impact
1. Past slowing loop-based products (products with reused content) (S_p)		Low contribution 1st Level "Avoiding wastage today"	Single in the past	Prolonging the useful lifetime of the product today to avoid waste
2. Past closing loop-based products (products with recycled content) (C_p)		Low contribution 1st Level "Avoiding wastage today"	Single in the past	Prolonging the useful lifetime of materials today to avoid waste
3. Past closing and slowing loop-based products (products with reused and recycled content) ($C_p S_p$)		Low contribution 1st Level "Avoiding wastage today"	Multiple in the past	Prolonging the useful lifetime of the product and materials today to avoid waste
4. Future slowing loop-based products (reusable (upgradable, reparable) products) (S_f)		Lower-medium contribution 2nd Level "Waste prevention in a short-term period in the future"	Single in the future	Prolonging the useful lifetime of the product in the future
5. Future and past slowing loop-based products (reusable products with reused content) (S_{pf})		Medium contribution 3rd Level "Waste prevention in a short-term period in the future and avoiding waste today"	Single in the future and past	Prolonging the useful lifetime of the product today and in the future

6. Future slowing and past closing loop-based products (reusable products with recycled content) ($C_p S_f$)		Medium contribution 3rd Level "Waste prevention in a short-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product today to avoid waste and also prolonging the useful lifetime of materials in the future
7. Future slowing and past closing and slowing loop-based products (reusable products with recycled and reused content) ($C_p S_{pf}$)		Medium contribution 3rd Level "Waste prevention in a short-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product today and in the future, and also prolonging the useful lifetime of materials in the future
8. Future closing loop-based products (recyclable products) (C_f)		Higher-medium contribution 4th Level "Waste prevention in a long-term period in the future"	Single in the future	Prolonging the useful lifetime of materials in the future
9. Future closing and slowing loop-based products (reusable and recyclable products) ($C_f S_f$)		Higher-medium contribution 4th Level "Waste prevention in a long-term period in the future"	Multiple in the future	Prolonging the useful lifetime of the product and materials in the future
10. Future closing and past slowing loop-based products (recyclable products with reused content) ($C_f S_p$)		High contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product today to avoid waste, and also prolonging the useful lifetime of materials in the future
11. Future and past closing loop-based products (recyclable products with recycled content) (C_{pf})		High contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Single in the future and past	Prolonging the useful lifetime of materials today and in the future

12. Future closing and past closing and slowing loop-based products (recyclable products with reused and recycled content) ($C_{pf}S_p$)		High contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product and materials today to avoid waste, and also prolonging the useful lifetime of materials in the future
13. Future closing and slowing and past slowing loop-based products (recyclable and reusable products with reused content) (C_fS_{pf})		High contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product today and in the future, and also prolonging the useful lifetime of materials in the future
14. Future closing and slowing and past closing loop-based products (recyclable and reusable products with recycled content) ($C_{pf}S_f$)		High contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of materials today and in the future, and also prolonging the useful lifetime of the product in the future
15. Future and past closing and slowing loop-based products (recyclable and reusable products with recycled and reused content) ($C_{pf}S_{pf}$)		The highest contribution 5th Level "Waste prevention in a long-term period in the future and avoiding waste today"	Multiple in the future and past	Prolonging the useful lifetime of the product and materials today and in the future

The product circularity contribution "*avoiding wastage today*" implies prolonging the useful lifetime of the product and/or materials to avoid waste today but without any future contributions from a long-term perspective. Hence, in terms of the circular product category, this can be mapped to past slowing and/or closing loop-based products. This level that leads to less-circular systems corresponds to the top of the lower triangle of the hierarchy shown in **Fig. 4**. Among three circular product categories of this level, namely S_p, C_p, and C_pS_p, a low single contribution in the past is inherent in the S_p and C_p categories and low multiple contributions in the past are inherent in the C_pS_p category (see Table 2). Appropriate product circularity profiles give a visual picture of these contributions. The product circularity contribution "*waste prevention in a short-term period in the* *future*" implies prolonging the useful lifetime of the product in the future. From the circular product category point of view, this can be mapped to the slowing loop-based products. This level corresponding to the second-from-top level in the lower triangle of the hierarchy illustrated in Fig. 4 denotes the lower-medium product contribution to the CE involving more circularity compared with the top of the triangle. Only one category of CE-related ‘future slowing loop-based products’ falls within this level with a lower-medium single contribution in the future. The next level "*waste prevention in short term period in the future and avoiding waste today*" denotes prolonging the useful lifetime of products today to avoid waste and thereby prolong the useful lifetime of products and/or materials in the future. This level covers three circular product categories that stand for future slowing and past closing and/or slowing loop-based products with a medium-level contribution of the product to the CE, corresponding to the lower triangle of the hierarchy. The focus at the level of "*waste prevention in a long-term period in the future*", i.e. the second-from-bottom level in the lower triangle shown in Fig. 4, is about prolonging the useful lifetime of materials in the future, which maps to future closing loop-based products, or prolonging the useful lifetime of products and materials in the future, which maps to future closing and slowing loop-based products. The level "*waste prevention in a long-term period in the future and avoiding waste today*" resides at the bottom of the hierarchy and connotes extreme circularity. It provides for prolonging the useful lifetime of products and/or materials today to avoid waste and thereby prolongs the useful lifetime of products and/or materials in the future. Six circular product categories belong to this level, one of which is recognized as a single high contribution to the CE in the future and past, while the other five product categories have multiple high contributions (see Table 2).

4.3 Product circularity data to quantify circular contributions

To make it possible to transform the product circularity contributions described above into circularity data, the formulations of these contributions need to be made more tangible, i.e. more convenient for quantification. Based on the essence of the quadrants of the "CSFP" model (see **Fig. 3**), we propose to represent the contributions as follows: recycled content (Quadrant I); design for recyclability (Quadrant II); reused content (Quadrant III); design for reusability (Quadrant IV) (**Fig. 5**).

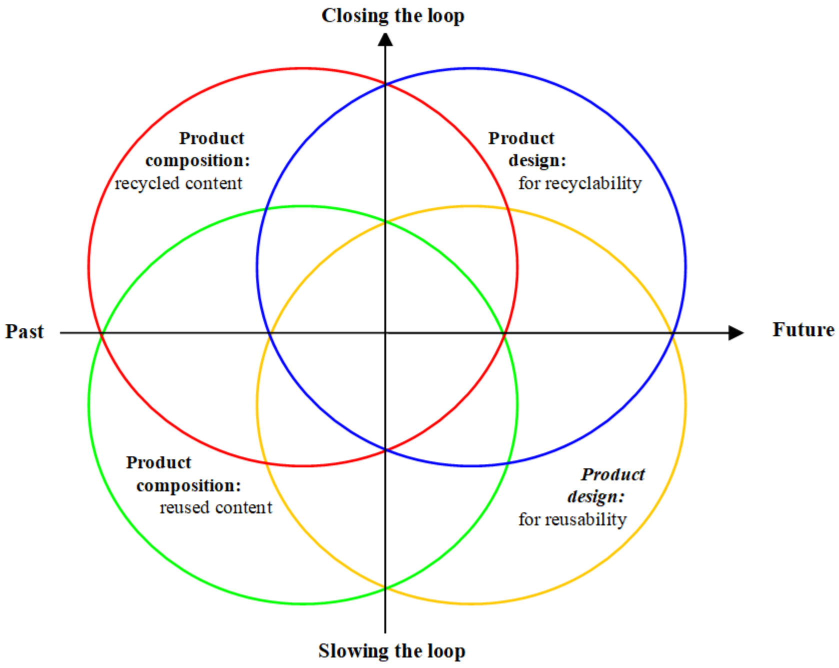


Fig. 5 Product circularity contributions in terms of composition and design

In order to quantify the listed contributions into circularity data, it is convenient and appropriate to use a scale from 1.0 to 0. In addition, to visualize the available circularity of a specific product on one side and reveal the unused circularity potential for the product on the other, it is reasonable to accompany the circular data with an allied profile, as illustrated in **Fig. 6**.

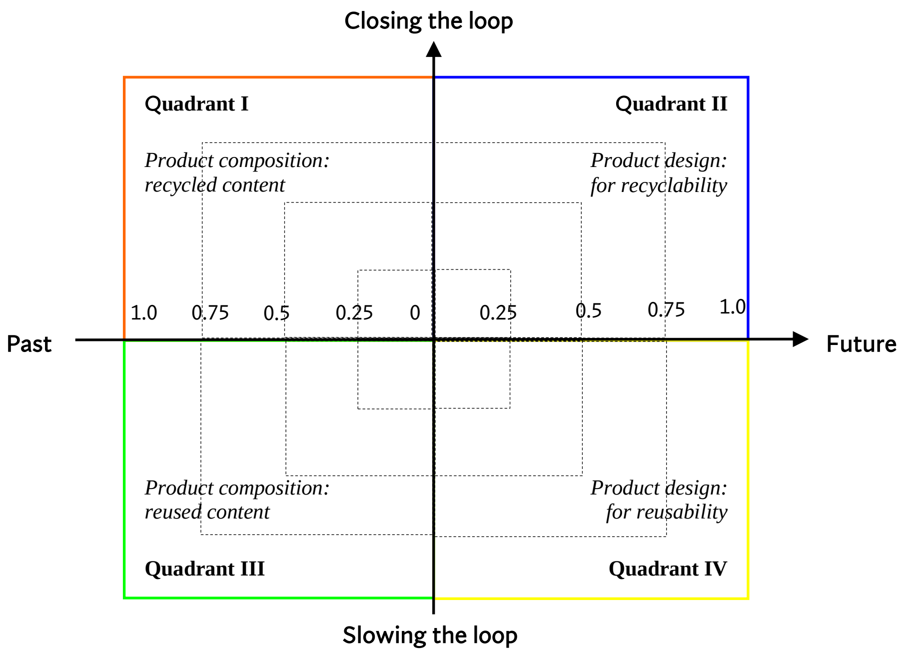


Fig. 6 Product circularity data profile for quantifying product circularity contributions

5. Discussion

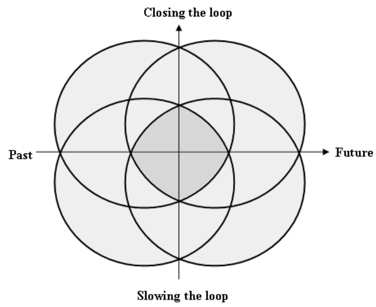
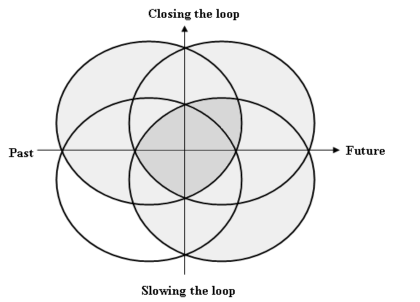
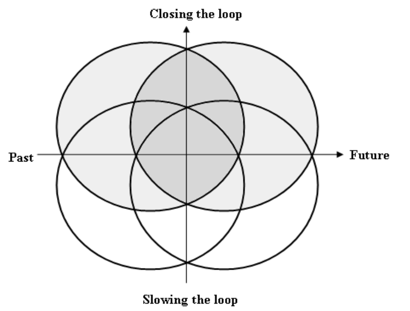
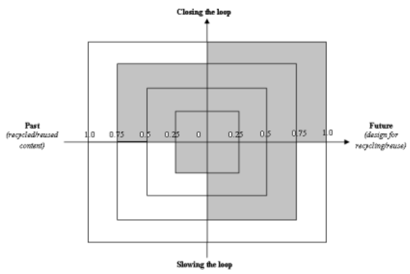
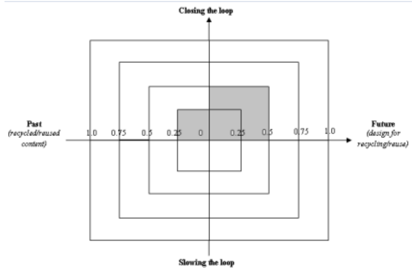
Several use-cases are presented below to show how the proposed categorization with appropriate product profiles and data profiles makes it possible to determine the degree of circularity of a product and reveal its available and unavailable circularity through the four parameters of the CSPF quadrant.

5.1 Circularity performance of smartphones across hypothetical companies

We do not provide the names of specific smartphone companies due to the lack of (i) data on smartphone composition (reused content and recycled content) and (ii) data on smartphone design for recyclability and reusability. Nevertheless, this example demonstrates the feasibility of using the developed categorization scheme and its practical significance for companies and designers in terms of understanding the available circularity potential of specific products and ways to utilize it.

Table 3 presents circularity contribution profiles according to the categorization scheme and also appropriate data profiles for smartphones produced by three hypothetical companies A, B, and C. According to the five-level inverted pyramid, the smartphones of all these companies have a high contribution to circularity through waste prevention in a long-term period (design for recyclability), among other factors. However, using the circularity data profiles makes it possible to more accurately determine and cross-compare the circularity or circularity contributions of each smartphone.

Table 3 Circularity performance for smartphones of hypothetical companies A, B, and C

COMPANY A	COMPANY B	COMPANY C
CIRCULARITY CONTRIBUTION PROFILES		
Product category: Future and past closing and slowing the loop-based product ($C_{pf}S_{pf}$) 	*Product category:* Future and past closing and future slowing the loop-based product ($C_{pf}S_{f}$) 	*Product category:* Future and past closing the loop-based product (C_{pf}) 
CIRCULARITY DATA PROFILES		
Contribution description: Design for Recyclability – 100% Design for Reusability – 75% Recycled content – 75% Reused content – 25% 	*Contribution description:* Design for Recyclability – 50% Design for Reusability – 75% Recycled content – 25% 	*Contribution description:* Design for Recyclability – 50% Recycled content – 25% 

Company A's smartphone has the highest contribution to CE, given the performance of several circular strategies in terms of future and past (see Table 3). The design of this smartphone means that 75% of all its parts and modules can be refurbished or remanufactured in the future, and all its materials are 100% recyclable. Moreover, by its composition, the phone contains 25% refurbished/remanufactured parts or modules, and 75% of the materials used are recycled materials. Hence, company A has performed recycling and reuse strategies today, thereby first saving the value of both product and material, but it has also created prerequisites through appropriate design for the performance of these strategies in the future. It is not certain that in the future, the value of this product and the materials used will be fully saved according to the circularity data profile, as the economic landscape of its territory is constantly changing. At the same time, the product circularity potential created by company A today makes it possible to save the value of both products and materials in the future.

Company B's smartphone has also a high contribution to circularity, as the product can be partially recycled and also reused for some parts or modules in the future due to the design for recyclability and reusability, respectively. At the same time, 75% of all materials of the smartphone are primary, and there is no reused content. In general, despite covering three quadrants of the model at the same time, the circularity data profile indicates a significant unused circularity potential compared to company A's smartphone. Company C's smartphone is in a similar situation, as it is 50% recyclable due to its design for recyclability and also 25% of the materials it uses are recycled, but there is again some unused potential in this case (see Table 3).

Beyond the hypothetical examples above, to demonstrate a high level of circularity among smartphones placed on the market, Dutch company Fairphones makes smartphones that focus on sustainability and circularity including repairability rather than performance. By composition, the Fairphone comprises some refurbished parts and secondary materials, thus avoiding wastage today. Further, due to superior design, characteristics such as repairability, recyclability, disassemblability, and reusability, make it possible to operationalize appropriate circular strategies in the future.

This discussion, although short, nevertheless highlights that the issue of design for (i) product upgradability as a short-term perspective and (ii) recyclability for all materials used as a long-term perspective is crucial for circular businesses, since it makes it possible to capitalize on EoL products and materials in the future. Societies as a whole have suffered major damages from environmental pollution due to undesirable outputs from the economic system as well at the stages of extraction and processing of primary resources. In fact, design for reusability and recyclability creates economic preconditions for launching circular business models. For instance, a company can create the prerequisites for refurbishing and remanufacturing to capitalize on EoL smartphones in the future as an alternative to new modules and parts without any "circular history". As a result, EoL products are now considered desirable outputs for the economic system and have become tradable rather than undesirable outputs or waste to be expelled from the economic system into the environment.

Assessing the circularity of different categories of electrical and electronic equipment warrants special attention due to the issue of biodegradable materials as an alternative to conventional or petroleum-based plastics. Globally, innovators have already proposed an array of original solutions for 100%-biodegradable materials that make great alternatives for pro-sustainability and pro-circularity strategies. An example of such an alternative is 100% biodegradable material made from spent coffee grounds, which has all the functional characteristics of conventional plastic and, for instance, could be a valuable alternative to plastics used in smartphone cases. Such material has already been tested in the production of sustainable glasses (spectacle frames) manufactured by Ochis (Ochis, 2022). The material is made of spent coffee grounds, natural oils, and a vegetable oil-based biopolymer used as a binder. It even has a special hydrophobic coating that makes it waterproof.

The following section focuses on products made from biodegradable materials.

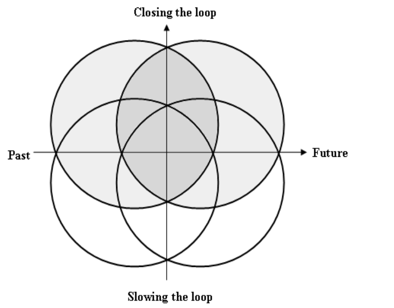
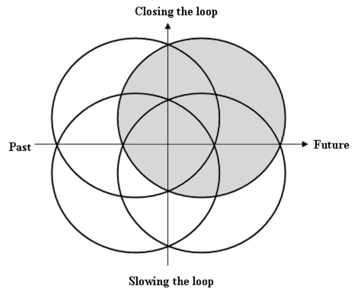
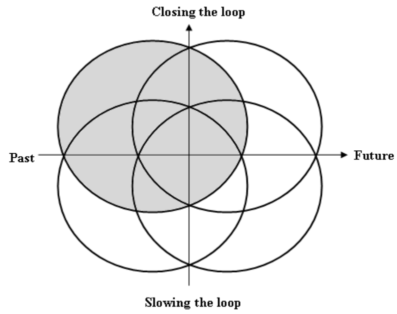
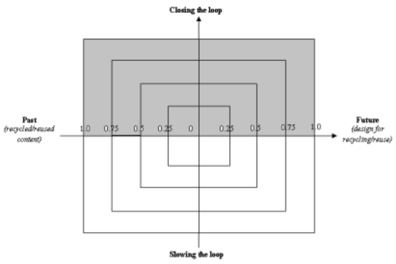
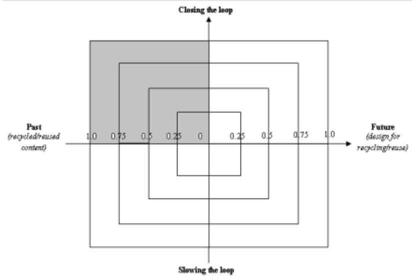
5.2 Circularity performance of bags

This subsection presents a comparison of the circularity of the bags typically used in retail chains and supermarkets as a use-case to discuss the aspect of the biodegradable content of the product in the circularity measurement using the proposed metric. The policy adopted in an increasing number of countries to move away from plastic-based bags is gradually leading to a search for more circular and eco-friendly alternatives, but these need to be assessed in terms of their real contribution to the CE.

Table 4 presents the circularity contribution profiles and appropriate data profiles for bags produced by three Ukrainian companies: Re-leaf, BIOC, and Polimer-praktik.

As seen in Table 4, among the presented companies, Re-leaf's bag has the highest contribution to circularity (the largest surface area for all quadrants), since the material for this bag is produced from fallen leaves (75%) and waste paper (25%) rather than primary paper, and is 100% biodegradable. The leaf processing technology, with subsequent paper production, was originally proposed by the Re-leaf startup (Re-leaf, 2022). The craft paper made by Re-leaf using this technology has a density of 80–90 g/m² and suitable physical and mechanical characteristics for use as packaging. Cellulose fibers from fallen leaves can be used as the main components or as adjuvants in the paper production process. Furthermore, products made from fallen leaves also present the unique advantage that there are no sulfur and chlorine compounds involved in the process. It takes 2.3 tons of fallen leaves to produce one ton of paper, which saves an average of 17 trees. In addition, the environmental benefits are a 15-fold reduction in water consumption and a 78.3% reduction in CO2 emissions (Re-leaf, 2022).

Table 4 Circularity performance of bags made by the companies Re-leaf, BIOC, and Polimer-praktik

"RE-LEAF"	"BIOC"	"POLIMER-PRAKTIK"
THE CIRCULARITY CONTRIBUTION PROFILES		
Product category: Future and past closing the loop-based product (C_{pf}) 	*Product category:* Future closing the loop-based product (C_f) 	*Product category:* Past closing the loop-based product (C_p) 
THE CIRCULARITY DATA PROFILES		
Contribution description: Organic waste content – 100% Biodegradability – 100% 	*Contribution description:* Biodegradability – 100% 	*Contribution description:* Recycled content – 100% 

BIOC's bag has a higher-medium level of circularity as it contributes to waste prevention in the long-term period in the future but without past contributions (see Table 4). BIOC's production technology involves 100% primary resources such as corn, and so there is no past contribution. The production of biopolymer serves as a platform for industrial processing of corn into 100% biodegradable biopolymer using a unique, innovative triple nanopolymerization technology, which affords a bio-compound or bioplastic with good physical-mechanical properties and a controlled period of biodegradability. In contrast to these two biodegradable alternatives, the Polimer-praktik proposes plastic-based bags produced from secondary plastic polymers. Polimer-praktik's bag can be characterized as having a low level of circularity, since it contributes to avoiding wastage today but without any circular contribution in a long-term perspective.

According to "A new Circular Economy Action Plan for a cleaner and more competitive Europe", design for reuse and recyclability, including in packaging, is becoming a key focus of efforts for more circular packaging. In a move to ensure that all packaging on the EU market is reusable or recyclable in an economically viable way by 2030, the Commission is set to revise Directive 94/62/EC to reinforce the mandatory essential requirements for packaging to be allowed on the EU market and to consider other measures, including driving design for reuse and recyclability of packaging and placing restrictions on the use of certain packaging materials for certain applications, in particular where alternative reusable products or systems are possible or where consumer goods can be handled safely without packaging (European Commission, 2020).

Mounting societal demand for reusable and recyclable packaging is now driving the generation of new solutions. Nevertheless, among the huge number of innovative ideas, there are a few novel ones that warrant special support and investment to accelerate the path from lab to market. Here we look at packaging ideas with the highest circularity impact. In order to reduce or even eliminate the generation of pseudo-solutions, for instance, 50% biodegradable packaging, the Action Plan measures together with government support, should aim to prone high-circularity-impact packaging in order to help such solutions survive in the marketplace. In Ukraine, for instance, there are relatively few such innovative solutions, and they are mostly at the prototype stage. However, one such solution warrants attention due to its huge pro-circularity impact: chitosan-based films. A method for obtaining chitosan-based films was presented by a team from the Institute of Applied Physics of the National Academy of Sciences of Ukraine (Kalinkevich et al., 2021). These films (illustrated in **Fig. 7**) can be used as packaging materials for foods, including food-contact materials that feature a smart film showing food freshness. Packaging made of this natural polymer is completely biodegradable. The polymer base of such films, chitosan, is a derivative of chitin, the second most common biopolymer in nature. Chitin is mainly sourced through crustacean processing wastes (ocean krill, shrimp, and crabs), and the fish processing enterprises in southern Ukraine generate a lot of seafood waste, which could become a valuable source of chitin.

(a) (b)

Fig. 7 Films based on chitosan. (a) Experimental sample of the film made from chitosan; (b) Smart film (Open source photos)

Briefly, to develop CE support policies with appropriate incentivization tools for more circular and eco-friendly packaging alternatives, policy-makers need to have a vision of possible alternatives based on sound science and with an understanding of the circular contribution and impact of each solution in order to promote better options in terms of sustainability and circularity. The methodology proposed here for ranking products, which has been described and discussed in the light of hypothetical and real examples above, can serve to give this vision.

5.3 Practical implications

This study proposes product-level circularity metrics for measuring a product's circularity performance together with appropriate data to afford a simple, clear, and concise tool for shared use by all actors in the value chain and all the possible stakeholders—including consumers—involved in a circular product system to drive the growth of circular products by building up circular potential for businesses. Of particular interest are circular data profiles on the actual level of product circularity, which are of undeniable practical value for (i) measuring the degree of circularity of a product based on the surface area of the data profiles, (ii) monitoring actual CE-related progress not only in saving the value of materials and products today but also in saving the value of both in the future, and (iii) standardizing product circularity data for use between and among stakeholders.

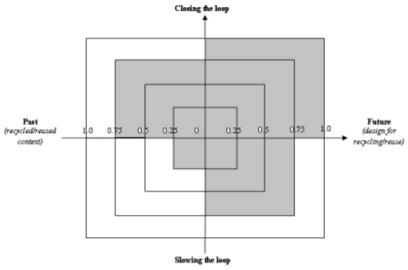
There are two points of discussion here: Is it possible to adopt a global measure of percent circularity based on the surface area of the data profiles? Is it possible to use the proposed models as maturity scales to augment the degree of circularity of a product?

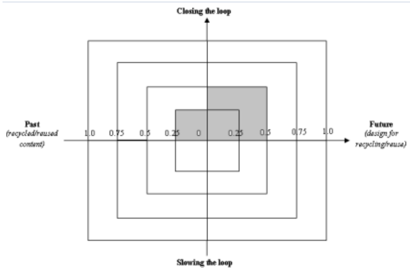
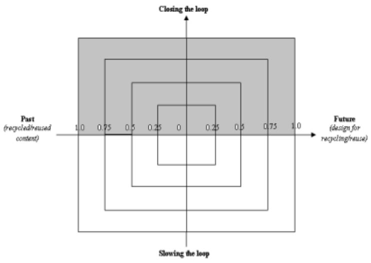
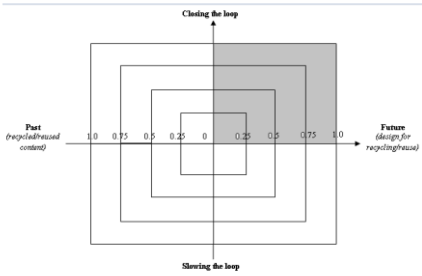
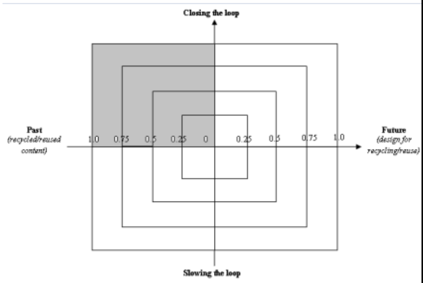
To address the first point, in the validation section we provide percentage calculations for the four quadrants separately to show how progressive the product is in each dimension. Even though past and future parameters do not have equivalent priority to design parameters and loop-slowing and loop-closing strategies do not share an equivalent priority for long-term perspectives, it is nevertheless possible to adopt a total percentage for a product as a *global metric* following the surface area of a data profile where each of the four quadrants accounts for a quarter of the circular impact. We can therefore use the proposed model as a maturity scale of a product's circularity not only from the perspective of each quadrant but also for all four quadrants combined. Along these lines, we anticipate our "CSPF" quadrant model as a starting point for computing a global circularity score for the product and providing its "CSPF" rating. We propose to adopt the simple arithmetic mean (formula (1)):

$$Circularity_{score} = \frac{1}{4}\left(\%\mathbf{Design}_{\mathrm{for}_{\mathrm{Recyclability}}} + \%\mathbf{Design}_{\mathrm{for}_{\mathrm{Reusability}}} + \%\mathbf{Recycled}_{\mathbf{content}} + \%\mathbf{Reused}_{\mathbf{content}}\right) \quad (1)$$

Table 5 presents product global circularity scores computed for the two use-cases we studied in the previous section.

Table 5 Product global circularity scores for the two cases

<table>
<tr><td colspan="3">Case 1: Circularity performance for smartphones of hypothetical companies</td></tr>
<tr>
<td>Company A
Circularity_grade = 68.75%

</td>
<td>Company B
Circularity_grade = 37.5%

</td>
<td>Company C
Circularity_grade = 18.75%

</td>
</tr>
<tr><td colspan="3">Case 2: Circularity performance of bags</td></tr>
<tr>
<td>"RE-LEAF"
Circularity_grade = 50%

</td>
<td>"BIOC"
Circularity_grade = 25%

</td>
<td>"POLIMER-PRAKTIK"
Circularity_grade = 25%

</td>
</tr>
</table>

With regard to the second point, when a product is rated on the four "CSPF" contribution scores, in particular, "Recyclability", "Reusability", "Recycled content" and "Reused content", the data profiles can serve to set improvement targets on dimensions that have not yet reached 100%. The presented use-cases demonstrate that this metric tool is easy to use and instructive to companies.

Furthermore, the global product circularity scores can be considered as a tool for comparing circularity performances of products within the same category-group but produced by different companies. The ranking of companies according to the circularity scores of their products can serve as a piece of background information for policy-makers to direct support towards companies that make products with a high circular impact, thereby increasing the growth of such products.

Finally, the provided framework helps to more effectively manage consumer engagement in the CE model and direct consumer behaviour towards more sustainable and circular consumption patterns and alternatives in the future. Considering the product acceptance phase as the initial point of the consumption stage, the contribution of the consumer as a customer was discussed in light of the proposed circular product categories in our previous study with further developing the measurement framework to assess the consumer contribution to the CE (Shevchenko et al., 2022).

6. Conclusions

The circular economy is an emerging issue that works to promote the responsible and cyclical use of resources that may contribute to a more sustainable future. However, the absence of adequate metrics and standards is a major barrier to the integration of resource efficiency requirements. This study attempts to develop a single product-level circularity metric for common use by all stakeholders involved in a circular product system for saving the value of materials and products for as long as possible. The original contribution of this study is the inclusive framework for measuring product circularity performance based on its integrated contribution to the operationalization of various configurations of circular strategies. The contributions of the present research are as follows. The CE-related product attributes model for characterizing circular products is proposed as a result of the synthesis of various main features of products generated by pro-circular businesses. Then, building on our "CSFP" quadrant model and the 15 derived circular product categories, we proposed and discussed the resulting 15 product circularity profiles. Furthermore, leading out of the quantification of circular strategy-related contributions originating from the "CSFP" quadrant model, we proposed a product circularity data profile coupled with a metrical scale for measuring circularity data and visualizing quantified circular contributions. Our findings contribute to a more accurate measurement of product circularity and a clearer comprehension of its integrated contribution to circular strategies running in parallel rather than singular strategies from only one side, and also to the standardization of product circularity data.

This study does come with some limitations. First, the inclusion criteria for the literature review part may have excluded some relevant research that was either in other languages than English or was not available at the time of data retrieval. In addition, this research is limited in its theoretical and methodological focus, since it was built on a literature review of the academic databases. However, we believe that the extensive scope of this review is strong enough to form a sound basis for our recommendations. Second, the proposed inclusive framework for measuring product circularity performance has not been tested in real-life settings, and thus this study remains limited in its recommendation. Third, although the framework presented covers all circular strategies to be operationalized in a long-term perspective, we did not focus on such issues as renewable energy and the safety of materials and substances used in manufacturing a product. However, the proposed product-level circularity metrics can readily be augmented with these parameters to become a more comprehensive assessment tool.

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