A CIRCULAR PRODUCT DESIGN TOOLKIT: METHODOLOGICAL BACKGROUND, BASIC PRINCIPLES AND BUILDING BLOCKS

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ABSTRACT

Circular product design has been recognised in the academia as a foundational step for companies to make circular business models functional and viable. In this regards, it is vital to have a quick-and-easy practical toolkit providing diagnostics and specific guidelines on product design in terms of circularity performance. The present paper announces a Circular Product Design Toolkit (CPD Toolkit) under development now, which aims at enhancing the circularity potential of an existing product by redesign. The following objectives are addressed. First, a brief review of existing approaches in the field of product-level circularity metrics and also available circular product design tools to clarify their purpose and practical value is conducted. Second, the scientific approach to assess a product circularity performance, previously developed, as a methodological background of the CPD Toolkit is outlined. Third, the basic principles and building blocks of the CPD Toolkit are briefly set out with further discussion in terms of possible presentation of information block as actual product circularity dataset and guideline part dealing with specific instructions for a company on how to progress in the circularity of the product produced.

Keywords: Circular economy, Design methods, Evaluation, product circularity, circularity metrics

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1 INTRODUCTION

Measurement approaches and metric tools for assessing circularity at organization level should be adequate and understandable for companies across various sectors of the economy to improve a product circularity performance. Recent studies in this field cover a wide range of topics including different circular strategies (Bracquené et al., 2020; Vanegas et al., 2018) or their configurations (Mesa et al., 2018; Boyer et al., 2021), mapping and testing CE indicators at the product level (Jerome et al., 2022), requirements to design a circularity measurement framework towards product performance assessment (Saidani et al., 2020). It is worth highlighting several product-focus indicators\ indexes most discussed in the scientific community, in particular Material Circular Index (Ellen McArthur Foundation, 2015), Circular Economy Indicator Prototype (Cayzer et al., 2017), Circular Economy Index (Di Mario and Carlo Rem, 2015) and Reuse Potential Indicator (Park and Chertow (2014). To quantify circularity at the product level, available metrics build on different types of units and dimensions namely mass (Haas et al., 2015), cost (Linder et al., 2017; Di Maio et al., 2017), longevity and frequency (Franklin-Johnson et al., 2016; Figge et al., 2018) etc.

To support companies in design a product in line with principal parameters of circular product, academia propose a wide range of circular product design strategies built on CE-related product's attributes, circularity metrics and relevant data. Key design approaches to circular products were explored by Aguiar et al. (2022). The recent study of Shahbazi and Jönbrink (2020) proposed a set of generic design guidelines across different circular strategies. The investigation of Bovea and Pérez-Belis (2018) was focused on identification of the design guidelines required for circular product design.

Although the solid advances made by scholars in the field over the past decade, there is a lack of a quick-and-easy practical toolkit providing diagnostics and specific guidelines on product design in terms of circularity performance. The present paper outlines a Circular Product Design Toolkit (CPD Toolkit) under development now, which aims at enhancing the circularity potential of an existing product by redesign. As opposed to available relevant tools, the novel CPD Toolkit evaluates a product circularity performance according to a maturity scale and provides a company by a guideline on how to launch circular strategies configurations working in parallel or in sequence rather than singular strategies.

The paper is organized as follows. In the Materials and methods section, a brief review of the existing approaches and tools in the field of CE product-level metrics and product design is conducted. The Results section outlines a methodological background underlying the CPD Toolkit. The section also sets out the basic principles and building blocks of the CPD Toolkit with further discussion of information block as actual product circularity dataset and recommendations block dealing with specific guidelines for a company. The conclusion section sets out the main contributions.

2 MATERIALS AND METHODS

The present study employs a semi-systematic literature review and a conceptual analysis to provide an overview and clarify practical value of existing approaches and tools in the fields of product-level circularity metrics and circular product design.

Among a wide range of studies on CE metrics, two state-of-the-art contributions worth be highlighted – a taxonomy of circular economy indicators developed by Saidani et al. (2019) and a multiple correspondence analysis of 63 metrics conducted by Parchomenko et al. (2019). Saidani et al. developed a need-driven taxonomy including 10 categories based on 55 circularity indicators to indicate their purposes and possible usages. The study of Parchomenko et al. provides a holistic picture of the current stock of CE related metrics based on comprehensive literature review. This study identified three main clusters of metrics in particular (i) a resource-efficiency cluster, (ii) a materials stocks and flows cluster, and (iii) a product-centric cluster. According to the findings obtained, the scholars highlight a poor integration of resource-efficiency and product-centric perspectives and also conclude that the product-centric and system-dynamic perspectives are least frequently assessed. According to Saidani et al. (2019) progress towards CE can be measured at different levels including macro level, company-level and micro- or product-level. The study of Bracquené et al. (2020) concluded that micro-level indicators are essential to capture the effect of potential interventions at product level where CE strategies are put into practice and we assume this argument.

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A literature review in the field revealed that there are few studies with direct focus on CE product-level metrics. The findings of recent influential studies are summarized below. Linder et al. (2017) proposed a value-based circularity metrics for a product produced by a company based on value chain costs. This circularity metric methodological approach was built on considering economic value as a basis for aggregating recirculated and non-recirculated parts into a combined measure of product circularity. The scholars conclude that such approach is valuable for leading to a uniform equivalent of all product parts, some of which provide specific contributions to a product circularity performance. The similar methodological metrics-related approach was proposed in the study of Di Maio et al. (2017) where the authors developed a value-based indicator for simultaneous measurement of resource efficiency and circularity in terms of the market value of "stressed" resources. The circularity in terms of longevity and frequency dimensions was explored in the studies of Franklin-Johnson et al. (2016) and Figge et al. (2018). The phenomenon of circularity reflects the time during which a resource provides value, which can by be captured by the longevity indicator according to the study of Franklin-Johnson et al. (2016). The authors highlighted that the CE measurement addresses resource longevity but not product longevity only. This idea was further developed by the same team in the study of Figge et al. (2018) by combining frequency and longevity dimensions of resource. The authors argued that frequency and length of time, a resource is used, determines resource efficiency. The scientists also highlight that frequency of resource use is not necessarily a parameter of its longevity as a resource could be used many times, but within a short timespan. The study of Boyer et al. (2021) considers the circularity in terms of three-dimensional scores, namely high material recirculation, high utilization, and high endurance in products and service offerings. In order to assess the performance of more circular complex product supply chains, Bracquené et al. (2020) proposed a new product circularity indicator to overcome the main limitations identified. The results of its application for washing machines show that the metrics is a useful to quantify the effectiveness of various circular strategies. In order to measure the circularity of product families, the study of Mesa et al. (2018) proposed to use a set of indicators related to material flow, reusability, reconfiguration, and functional performance. To assess the ease of disassembly of products, the study of Vanegas et al. (2018) developed a tool “eDiM” (ease of Disassembly Metric) which employed involved a calculation sheet to determine the disassembly time considering the sequence of actions and basic information about a product produced by a company.

Exploring the issue of testing the validity or reliability of available product-level circularity metrics, the scholars conclude that despite numerous methods and tools available in academia, only few studies have tested them on real industrial cases and, while if attempting to validate, the metrics have revealed serious limitations and shortcomings (Jerome et al., 2022; Linder et al., 2020; Bracquené et al., 2020).

Based on the terminology of slowing, closing, and narrowing resource loops, a framework of circular product design strategies to guide designers and business strategists was developed by Bocken et al. (2016). A conceptual framework for circular product design was developed by Mestre and Cooper (2017), which has driven by the following four types of multiple loops strategies: design to slow the loops, design to close the loops, design for bio-inspired loops, and design for bio-based loops. In reliance on Walter Stahel's Inertia Principle as the general principle in circular product design, a typology of approaches for Design for Product Integrity has been developed by Den Hollander et al. (2017). The study of Bakker et al. (2014) investigates a set of product life extension strategies with further justification these strategies applications in terms of tailored approaches. The tool to evaluate a product circularity potential at the stage of product design was developed and tested at four companies in Nordic countries (Albæk et al. 2020). The scholars concluded that proposed tool is useful in decision-making process in the early stages of product development. The study of Aguiar and Jugend (2022) proposes a maturity matrix for the gradual adoption of the circularity in the new product development process. Saidani et al. (2020) explores the availability of product related circularity indicators for product design. As a result, the four product-level circularity indicators were tested on the engineering design process. The research conducted by Kwak and Kim (2011) presents a quantitative model for assessing product family design in terms of end-of-life perspective which allows identifying an optimal strategy for managing product take-back and EoL recovery, thereby providing profitability in end-of-life management.

In light of the studies on product-level circularity metrics and product design approaches and available tools, the present analysis finds that there is no a quick-and-easy practical toolkit for assessment and visualization of the integrated circular contribution of various configurations of circular strategies

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working in parallel or in sequence (diagnostic block), and also providing specific guideline on product design in terms of circularity performance based on this assessment (recommendation block). The next section outlines a methodological background of the novel CPD Toolkit, currently under development, which aims to address this issue.

3 RESULTS AND DISCUSSION

3.1 Methodological background of CPD Toolkit

To assess a product-level contribution to the CE, the study of Shevchenko et al. (2022a) justified that due to the difference in the contribution to closing the loop (products with recycled content and recyclable products) or slowing the loop (products with reused content and reusable products), and also the difference in the period of such contribution, namely, future closing or slowing (recyclable or reusable products) or past closing or slowing (products with recycled or reused content), it is necessary to introduce a single categorization of CE-related products. In this regard, the "Closing–Slowing Future–Past" ("CSFP") quadrant model was developed by the authors based on combination of the principal attributes of CE-related products such as "the type of CE loops" and "the time of waste prevention" (Fig.1). The "CSFP" quadrant model illustrates four quadrants, in particular I quadrant – product with recycled content (past closing the loop), II quadrant – recyclable product (future closing the loop), III quadrant – reusable product (future slowing the loop), IV quadrant – product with reused content (past slowing the loop).

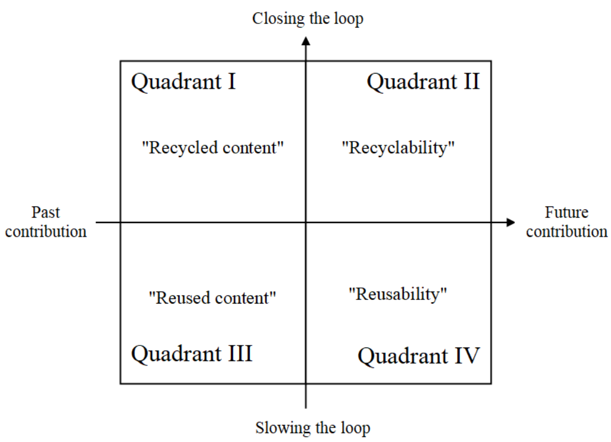

Figure. 1 "Closing–Slowing Future–Past" quadrant model (Shevchenko et al 2022a)

A single categorization of CE-related products was developed based on the "CSFP" quadrant model (Shevchenko et al. 2022a). Table 1 illustrates fifteen circular product categories as a result of all possible combinations of product attributes namely future and past, closing and slowing the loop, respectively. This study also proposed a five-level pyramid differentiating fifteen categories of circular product based on the contributions to the CE ranging from less to more circular products.
In continuation of the study on product categorization, the next research of Shevchenko et al. (2022b) provides product circularity data quadrant to quantify and visualize circular strategy-related contributions (Fig.2).
The data quadrant mentioned can be used as a maturity scale of a product's circularity. In this regard, the scholars consider the model as a starting point for computing a global circularity score for a product. To calculate the global product circularity score, it is proposed to adopt the simple arithmetic mean by formula 1 (Shevchenko et al. 2022b):

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

When a product is rated on the four "CSFP" 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%.

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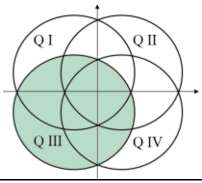
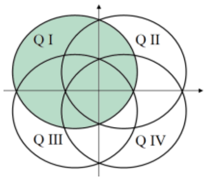
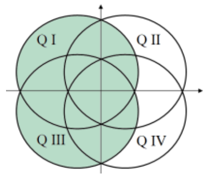
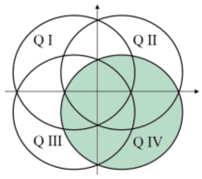
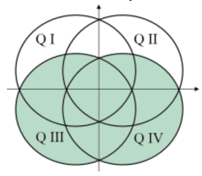
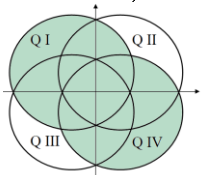
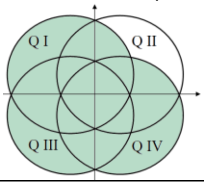
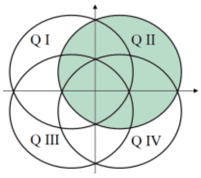
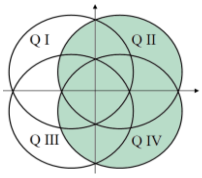
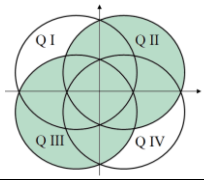
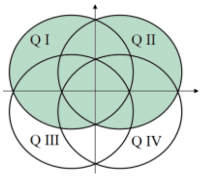
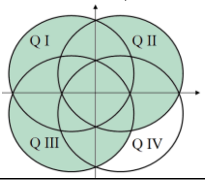
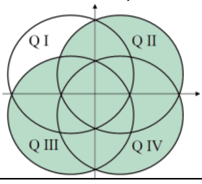
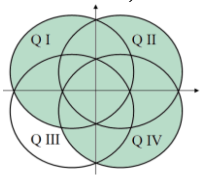
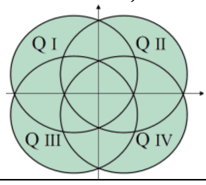
Table 1. Product circularity profiles according to fifteen circular product categories

No1: Past slowing loop-based products (products with reused content) 	No2: Past closing loop-based products (products with recycled content) 	No3: Past closing and slowing loop-based products (products with reused and recycled content) 	No4: Future slowing loop-based products (reusable (upgradable, reparable) products) 	No5: Future and past slowing loop-based products (reusable products with reused content) 
No6: Future slowing and past closing loop-based products (reusable products with recycled content) 	No7: Future slowing and past closing and slowing loop-based products (reusable products with recycled and reused content) 	No8: Future closing loop-based products (recyclable products) 	No9: Future closing and slowing loop-based products (reusable and recyclable products) 	No10: Future closing and past slowing loop-based products (recyclable products with reused content) 
No11: Future and past closing loop-based products (recyclable products with recycled content) 	No12: Future closing and past closing and slowing loop-based products (recyclable products with reused and recycled content) 	No13: Future closing and slowing and past slowing loop-based products (recyclable and reusable products with reused content) 	No14: Future closing and slowing and past closing loop-based products (recyclable and reusable products with recycled content) 	No15: Future and past closing a nd slowing loop-based products (recyclable and reusable products with recycled and reused content) 

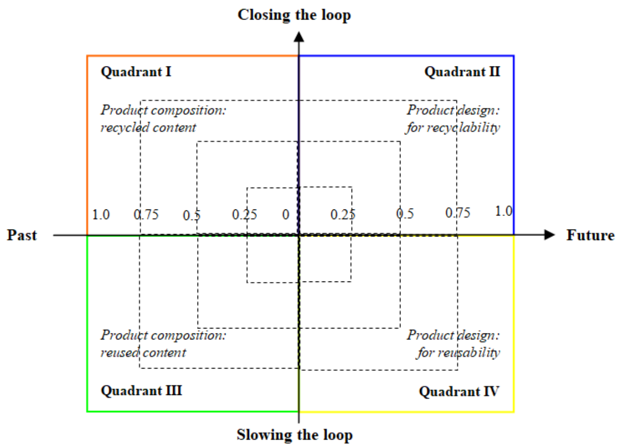


Figure. 2 Product circularity data quadrant (Shevchenko et al 2022b)

The following section outlines the content of the CPD Toolkit, under development now, building on fifteen circular product categories mentioned. The CPD Toolkit, as opposed to available circularity metric-related tools, evaluates a product circularity performance according to a maturity scale and provides a company with the guidelines on how to select and implement relevant circular strategies.

3.2 CPD Toolkit: building blocks and basic principles

The CPD Toolkit will include two building blocks, in particular a Diagnostic block and a Guideline block. Application of the Toolkit consists in filling the diagnostic sheets by a company with appropriate data about a product's contributions to "Recyclability", "Reusability", "Recycled content"

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and "Reused content" and also additional basic information about a product. As a result of filling out, the Toolkit will generate the Guideline based on actual product circularity dataset with appropriate recommendations on product design in terms of circularity performance.The CPD Toolkit Diagnostic block will include actual product circularity dataset, in particular the following information: (i) product circularity profile corresponding to a circular product category identified (see Table 1); (ii) product circularity data quadrant including information about available circularity potential (see Fig. 2); (iii) global product circularity index (see formula 1); (iv) additional basic information.
The CPD Toolkit will be accompanied by general guidelines corresponding to fifteen circular product categories and other basic dataset listed above. To understand all possible product-level circular strategies which can be applied by a company, we propose to use a five-level pyramid classifying fifteen categories of CE-related products, set out in the study of Shevchenko et al (2022a). These 5 strategies will be refined and detailed in the near future by applying the model on real products. Dealing with the CE-related contributions, this pyramid has the following five levels of product circularity, from less circular up to more circular: (i) avoiding wastage today (No1, No2, No3); (ii) waste prevention in a short-term period in the future (No4); (iii) waste prevention in a short-term period in the future and avoiding waste today (No5, No6, No7); (iv) waste prevention in a long-term period in the future (No8, No9); (v) waste prevention in a long-term period in the future and avoiding waste today (No10, No11, No12, No13, No14, No15). In this line, we propose to use these five levels of the hierarchy as possible product-level circular strategies (Fig. 3) which are valuable for developing the CPD Toolkit Guideline block.

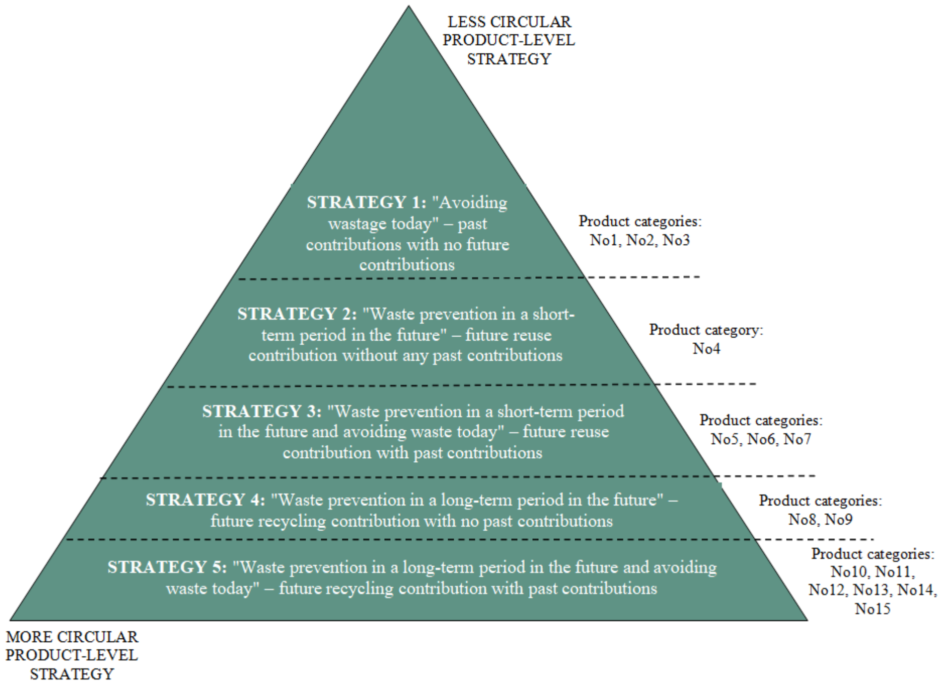

Figure. 3 Product-level circular strategies hierarchy according to fifteen categories of circular products (developed based on Shevchenko et al 2022a)

To justify circular strategies as a background of the Guideline block, the product circularity data profile (see Fig. 2) should be applied. Depending on the degree of use of the available product circularity potential, three possible options for guidelines can be considered namely:
(i) Jumping to a next product category;
(ii) Stay within the same category to use available circularity potential;
(iii) Both options to increase the circularity percentage within new and already run quadrants.
To elucidate the mentioned options, Fig. 4 shows various conditional examples of product circularity data profiles. The examples of the profiles (a), (b) and (c) demonstrate the fully utilized available potential within appropriate quadrants, hence actualize the need to use the potential of a new quadrant/quadrants. The examples of the profiles (d), (e) and (f) showcase the partly used potential within appropriate quadrants, hence actualize the need to use available circularity potential within quadrant/quadrants already run or/and use the potential of a new quadrant/quadrants.

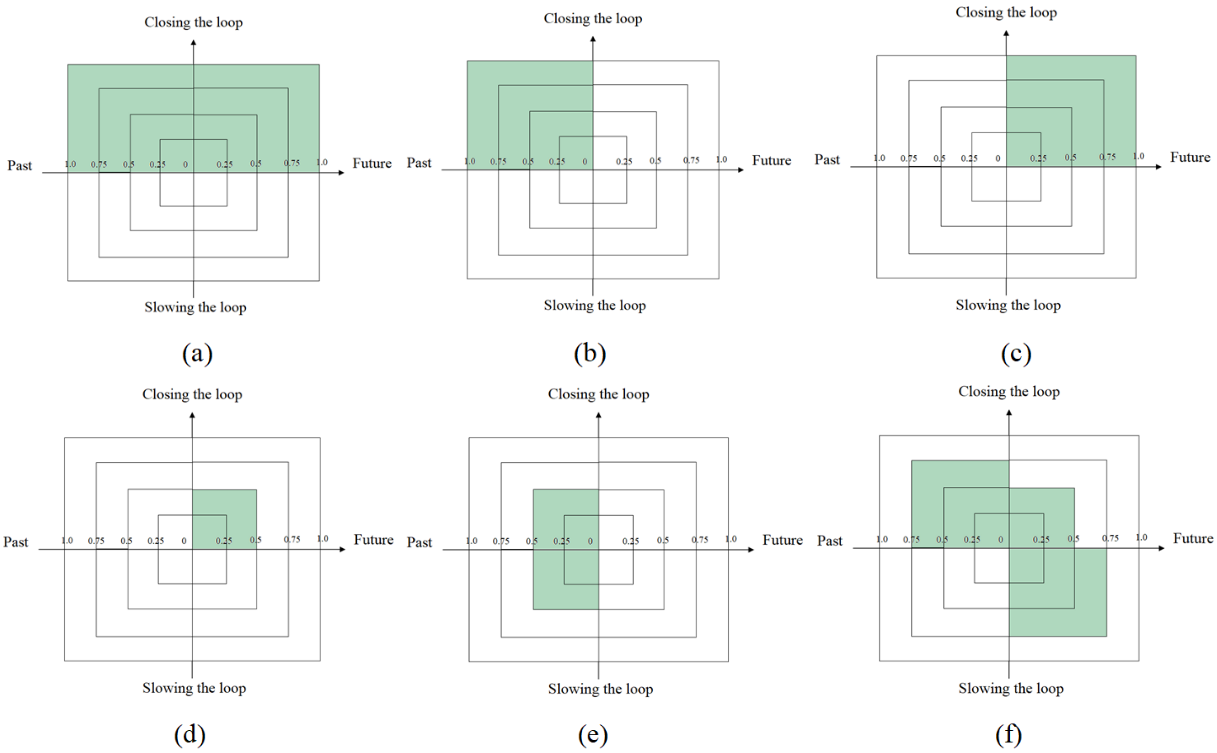

Figure. 4 Conditional examples of product circularity data profiles

3.3 A simple case study to illustrate the CPD Toolkit principle

To illustrate the possible uses of the CPD Toolkit, a simple example is proposed in this section. Three different models of jeans pants from three different brands are considered, and information are gathered from websites. All evaluations proposed in this section are made by the authors, without any contributions from the companies, and based only on publicly available information and hypotheses. They do not reflect the reality and are used only to illustrate the CPD Toolkit. The three models are:

- Model No1: the first model of jeans is a fictive low-cost and fast-fashion model, with several materials (denim fabric made from cotton, metal rivets and buttons, thread, label). Only primary materials are used, and no particular focus is made on the end-of-life.
- Model No2: the second model of jeans is the "Circular Levi's 501" model sold by the American company Levi Strauss & Co. The denim fabric used is made from 60% of organic cotton, 24% of wood pulp from sustainability managed forests, and 16% of Circulose (recycled fabric made from discarded cotton textiles like worn-out jeans) (Levi Strauss & Co, 2022). No information is provided regarding the recycled origin and recycling potential of other materials (rivets and buttons, thread, label), that are assumed to be from primary materials in this case study. Levi's is also claiming to actively work on lifetime extension and reuse (rental, repair, resale through the program Levi's SecondHand, upcycling collaborations), and recycling.
- Model No3: the third model of jeans is the "Infinite jeans" produced by the French company 1083. It is made only of 100% recycled polyester (mono material used for denim fabric, buttons, thread). It is 100% recyclable and a deposit of 20€ is included in the price of the pants and returned to the client when he/she brings them back at the end-of-life (1083, 2022).

Based on these data, the product circularity data profile of each model is calculated, and results are shown on Figure 5. The values are calculated as follows:

- Quadrant I (recycled content): model No1 does not include recycled content (0%). Model No2 includes 16% of recycled content (considering only the fabric and considering that the mass of the other component is negligible), while model No3 is made from 100% of recycled content.
- Quadrant II (recyclability): no particular focus on recycling is made by the company producing model No1; however national textile recovery and recycling programs may exist in the country where the product is used (for example in European countries); for the stake of this example, the value is arbitrarily set to 25% for model No1, assuming that the product may be voluntarily given to another person, or send to a collection point, and then reused or recycled. For model No2, the value is set to

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75%, as the company is proposing recycling program, but information is lacking to assess the materials used for the components except the denim fabric itself. For model No3, the value is set to 100% as only one recyclable material is used, and the company is actively recovering the product with a financial incentive for the customer.
- Quadrant III (reused content): none of the three models is using reused content (0%).
- Quadrant IV (reusability): value for model No1 is set to 25%, for the same reasons used for Quadrant II, while value for model No2 is set to 75% as the company is proposing programs to extend the lifetime, repair, resale or upcycle the product. Finally, for model No3, as no incentive is proposed by the company, value is set to 25%, with the same justification than model No1.

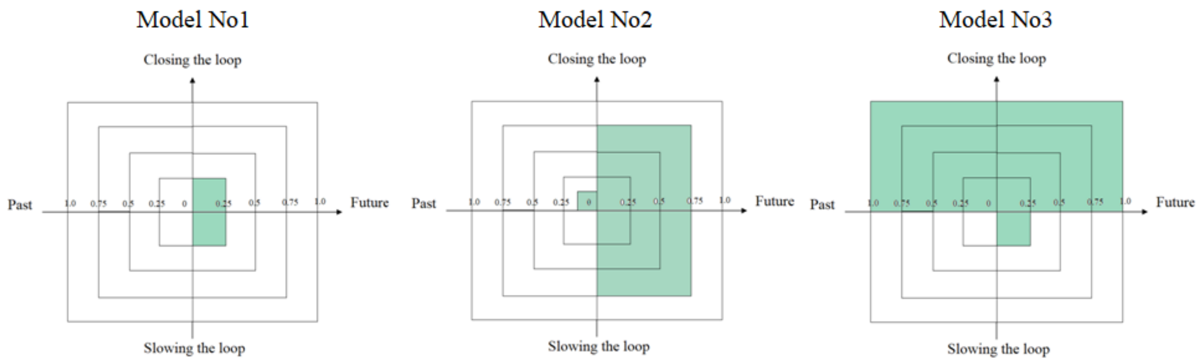

Figure. 5 Evaluation of product circularity data profiles for the three jeans models

Results show that the three models of jeans have quite different circularity data profiles. The global circularity scores calculated with formula 1 are as follows: model No1: 13%; model No2: 42%; model No3: 56%. According to Table 1, model No1 is included to the circularity profile No9 (Future closing and slowing loop-based products (reusable and recyclable products)), but with a poor level of completion (25% for both targeted quadrants). Model No2 and model No3 are included to the circularity profile No14 (Future closing and slowing and past closing loop-based products (recyclable and reusable products with recycled content)), with very different levels of completion: for model No2: a high level of completion (75%) for Quadrants II and IV, but a low level for Quadrant I (16%); and for model No2: a extreme level of completion (100%) for Quadrants I and II, but a low level for Quadrant IV (25%).
This simple example shows that the tool is able to notably differentiate products on a same market, but also that this evaluation on the four quadrants and the global circularity scores lead to recommend different and customized circular strategies, selected in Figure 3. For example, model No1 is currently under the Strategy 4 ("Waste prevention in a long-term period in the future"), but only from contextual reasons at a national level. The company can therefore progress on every quadrant. Model No2 and model No3 are currently acting under Strategy 5 ("Waste prevention in a long-term period in the future and avoiding waste today") with very different positionings. The company producing model No3 should probably act in Quadrant IV in order to promote reuse of products before sending them to recycling, but the business model of this very small company may weaken. On the contrary, the company producing model No2 should keep on going efforts to maximize reuse and recycling (that may be very effective as this is a well-known international brand), but also increase the rate of recycled content.
It is interesting to notice that Quadrant III is hard to reach for a specific model on this market. Company producing model No2 has developed a second-hand platform to sell reused products, but this is not captured in Quadrant III as we are assessing here a specific brand-new product.

3.4 Discussion

The case study proposed in this paper illustrates the ability of the tool to capture differences between products on a same market. However, the product used for the case study is very simple, with few components and materials. Future work will consider more complex products with multiple components and materials, that will allow both to clarify and design in detail the rules and Sheets block to assess the circularity score of one or several products on a same market, but also to design in detail the Report block with that will connect this circularity assessment with precise recommendations of circular strategies that can be followed by the company. One major challenge will be to enrich the strategies proposed in Figure 3 with "Design for circularity" methods and tools from the literature or originally designed by the authors.

Also, the product circularity data quadrant model only focuses on slowing and closing the loop; it is designed to capture other information regarding the sustainability of the products or companies producing the assessed product. For examples, some actions proposed by the company producing model No2 or model No3 are contributing to sustainability (for instance model No2: "metal trims don't use electrical plating process", or less use of water to produce the jeans thanks to a innovative technology; or model No3 is produced and sold in France, limiting the impacts due to transports) are note considered with this tool. Therefore, the CPD Toolkit may be complemented with other evaluation tools focused for example on environmental or social impacts. In the next months, the authors plan to illustrate and test the different steps of the methodology with multiples examples from different sectors, and to collaborate with a French start-up in the forthcoming months to develop and apply the full CPD Toolkit.

4 CONCLUSIONS

A brief review of existing approaches and tools in the field of product-level circularity metrics revealed that there is no quick-and-easy Toolkit to assess a product circularity performance in terms of circular strategy configurations and also provide guidelines for a company on how to progress in the circularity of a product produced. The present paper announces a Circular Product Design Toolkit (CPD Toolkit) under development now which is intended for guiding a company on how to improve a product circularity performance. The paper outlined the methodological background underlying the CPD Toolkit and also elucidated basic principles of its work, originality, significance, and practical implication. The CPD Toolkit was discussed in terms of possible presentation of information block as actual product circularity dataset and recommendations block dealing with specific guidelines for a company. Future work will make this toolkit more operational by applying, testing, and validating it on several existing products.

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