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A Systems-based Framework for Product Circularity Assessment

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Abstract. One of the key aspects of Circular Economy (CE), particularly when focusing on the product level, lies in its emphasis on designing products to facilitate the circulation of resources and maximize value throughout their entire lifecycle. To effectively develop such products an understanding of the characteristics of circular products (CP) is needed. Adopting a systems perspective that considers the total lifecycle and stakeholders involved and recognizing interdependencies among them is essential for identifying factors that characterize CPs. Existing methods for assessing product circularity do not identify all factors that characterize CPs and have limitations in the measurement methods proposed, leading to poor industry adoption. This research aims to develop a systems-based framework with clearly defined attributes, indicators, and metrics for product circularity assessment (PCA) to facilitate more effective design practices for CPs. A two-pronged approach, with industry engagement, is followed to address this gap: first, a systematic analysis of literature is conducted to identify key attributes and establish a clear foundation of what constitutes a CP; secondly, a comprehensive examination of indicators and metrics to evaluate the attributes is undertaken. This paper presents the preliminary systems-based framework for PCA with example attributes, indicators, and metrics, specifically for consumer electronic product circularity evaluation and directions for further research.

Keywords: Circular Economy, Circular Products, Product Circularity.

1 Introduction

The excessive and irresponsible use of resources for manufacturing products, and existing practices of their disposal at end-of-use, have resulted in significant adverse effects on the environment and society [1, 2]. To sustainably meet the needs of a growing global population striving for higher living standards, a shift from the linear economy's 'take-make-use-dispose' practices to a more Circular Economy (CE) that focuses on regenerative and restorative approaches through closed-loop material flow is necessary. For this transition to occur, CE implementation must be grounded in and driven by its application at the product level [3].

CE principles must be incorporated into the design, manufacturing, and lifecycle management of products. Without a dedicated emphasis on integrating the CE principles during product design, i.e., to develop circular products (CPs), the benefits of circularity cannot be effectively derived across meso (e.g., industrial systems) or macro (e.g., cities, regions, or countries) levels. Product designers/engineers assume the role of change agents within CE [4] and need to be equipped with the necessary tools to make effective decisions to design CPs during product development process (PDP).

Sustainable manufacturing involves the application of 6Rs (Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture) [5] and total lifecycle consideration to ensure triple bottom line (TBL) benefits are optimized. By collectively implementing sustainable manufacturing practices at the product, process, and system levels additional benefits can be generated for all stakeholders, leading to more sustainable value creation [6]. CPs play a pivotal role in paving the path towards sustainability through increasing economic prosperity, closed-loop material flow, and reduced environmental impacts. As shown in Fig.1, CPs can serve as one of the catalysts for the development of more sustainable products, ultimately leading to sustainable value creation for all stakeholders [6, 7].

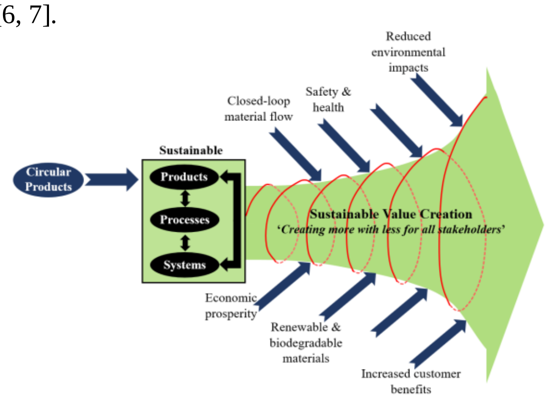

Fig. 1. Circular products as a path to sustainable value creation.

To effectively design such products, it is vital to have a concrete understanding of what constitutes a CP, and how to measure and assess product circularity. Numerous studies have proposed frameworks and metrics to assess product circularity. Despite extensive efforts, limitations persist [8]. Prior studies focusing on CPs and circular product design (CPD) have identified numerous and varied characteristics to describe CPs, but the consistency among them is lacking [9]. Limited awareness of benefits, challenges to operationalizing through CPD, misaligned regulations, and conflicting priorities may hinder widespread adoption of CPs. A clear understanding of key characteristics of CPs and a well-defined method for their assessment are still needed to operationalize the design of CPs. This paper presents a systems-based framework with clearly defined attributes, indicators, and metrics for product circularity assessment (PCA) to address this gap.

2 Overview of Methodology

A two-step approach is followed in this study to develop the PCA method (see Fig. 2). The first step focused on identifying attributes that characterize circular products. An attribute is defined as a constitutive characteristic that describes the desired features/properties of CPs [10]. The second step focused on a comprehensive examination of indicators and metrics to evaluate each of the selected attributes. Indicators provide valuable information about performance or describe the state of a specific attribute [11], while metrics offer more detailed information regarding the means of measuring these indicators [12]. The indicators and metrics relevant for evaluating circularity of a given product can highly vary from one industry to another. Therefore, to ensure industry relevance as well as for ease of verification and validation, consumer electronics products (CEP) are chosen as the use case and experts from the consumer electronics industry were engaged during both the steps.

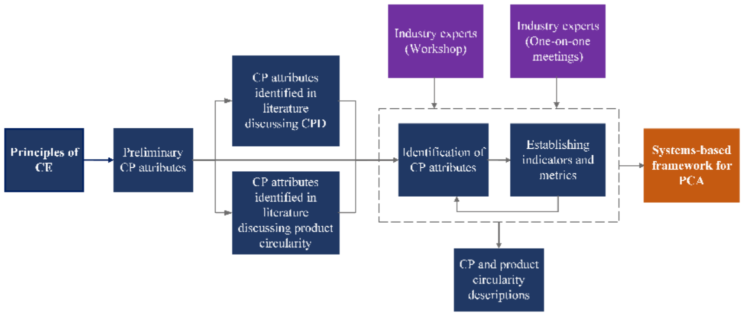

Fig. 2. Methodological process to design the systems-based framework for PCA.

Identification of attributes: Numerous definitions of the CE have been presented in the literature, often leading to conflicting viewpoints [3, 13, 14]. To develop a systems-based framework, efforts were initially dedicated to establishing a comprehensive understanding of the core tenets of the CE concept, delineating the scope to be considered for CPs. Then, a rigorous analysis of literature focused on CPs, CPD, and methods for evaluating product circularity. This process aimed to determine a list of CP attributes (as depicted in Fig. 2).

Establishing indicators and metrics: Upon determining the attributes, a comprehensive examination of indicators and metrics was undertaken. This process was also informed by reviews of scientific literature and industry reports. The metrics compiled are intended to serve as examples as they are likely to vary based on the industry and product being evaluated.

Industry stakeholders from the consumer electronics sector were actively engaged in the process first through workshops and then through one-on-one meetings to provide feedback (see Fig. 2). The entire process involved iterative refinement and continuous improvement of the descriptions for attributes, indicators, and metrics to ensure clarity and accuracy of the information conveyed for each of them.

3 Review of Circular Product Attributes

In authors' previous work [9], a comprehensive review of CP attributes identified in various literature sources was presented. Studies have pointed out the importance of designing products for multiple lifecycles, with opportunities for servitization and lifecycle extension and incorporating various value recovery strategies (e.g., recover, reuse, remanufacture, recycle), etc., to promote increased circularity. The significance of ensuring environmental and economic benefits through CPs [15], assessment over all lifecycle stages [16], incorporating strategies to enable material recirculation, utilization, and endurance in products and services [17], and many others have also been identified as relevant attributes. Space limitations do not permit a comprehensive discussion here; more details can be found in [9].

A comprehensive list of CP attributes, including those described above, were identified through a detailed literature review to develop the PCA framework. To address the variability and inconsistencies in the use of terms, the attributes were grouped based on their similarities in meaning. The results were then evaluated using a Pareto analysis, to prioritize and identify 20% of the attributes that can be considered as representative of describing the majority, or 80%, of characteristics of CPs. This analysis, shown in Fig. 3, highlights the attributes most frequently referenced in the literature as characteristic of CPs.

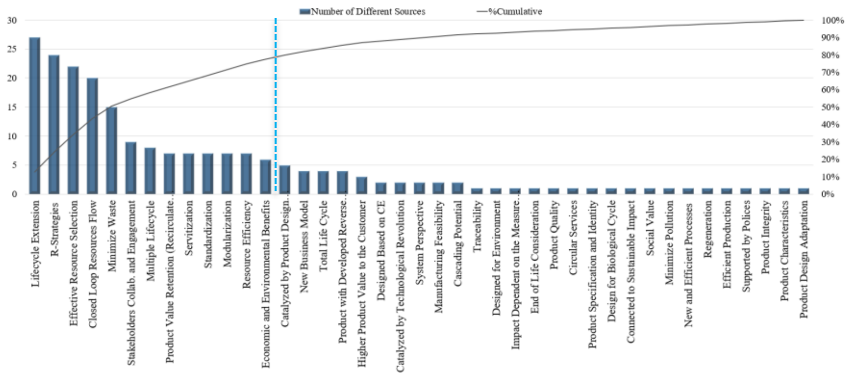

Fig. 2. Pareto analysis of CPs attributes.

4 Systems-Based Framework for PCA

The analysis presented in the previous section led to the definition of thirteen different attributes most frequently referenced in published literature as constituent characteristics of CPs. Following a closer examination of the criteria pertaining to each, these attributes can be classified into three distinct groups: i) Drivers/Enablers, ii) Outcomes, and iii) Benefits and Implications. The drivers and enablers encapsulate the requirements to design, develop and deploy CPs. In other words, the drivers and enablers are capabilities necessary to offer CPs. The presence of such capabilities, however, does not automatically lead to CPs. The actual design and deployment of CPs, using forward and reverse supply chains and participation of all stakeholders, is what leads to the circular flow of resources necessary for transition to a CE.

Thus, the attributes belonging to the second group—Outcomes—denote the actual characteristics that are exhibited by the products designed, manufactured, used, and managed at end-of-life (EoL). When the drivers and enablers are utilized to deploy CPs, it can bring about numerous economic, environmental, and societal benefits. Designing and launching CPs is meaningless unless such benefits can be derived. However, inevitably trade-offs exist among them as well. The third category of attributes—Benefits and Implications—represent the potential consequences that arise from operationalizing CPs. In summary, the 'Drivers and Enablers' facilitate operationalizing the requirements to achieve the 'Outcome' of CPs which can bring about various 'Benefits and Implications'. From an industry perspective, the goal of developing CPs is to maximize the benefits and minimize any negative implications. The attributes that are drivers and enablers (D&E) will then become 'levers' that must be adjusted, to manage the benefits and implications (B&I), as desired.

As shown in Fig. 4, these attributes and the interdependent relationships among them offer a systemic framework to develop an approach for product circularity assessment (PCA) and for its industry adoption by identifying D&E to achieve desired B&Is.

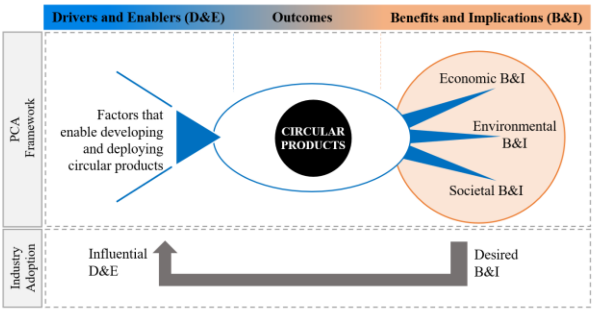

Fig. 3. Systems-based framework for PCA.

5 Attributes, Indicators and Metrics for PCA

For each key attribute identified from the Pareto analysis, different sources of literature were reviewed to determine the most suitable terminology that clearly conveys the constitutive characteristic, eliminating ambiguity. The identified attributes, along with a subset of literature sources (due to space limitations) recognizing their relevance, are organized into the three categories (Fig. 4 and presented in Table 2).

Three main attributes are considered as drivers and enablers: design/redesign to facilitate circular characteristics (e.g., modularity, easy maintenance, and repair), effective resource selection, and stakeholder consideration and engagement. In the outcomes category, CPs are defined by five main attributes: incorporate value recovery, extended product use-life, incorporate closed-loop resources flow, facilitate multiple lifecycles, and minimize waste. Five attributes are identified for the benefits and im-

plications category: optimized resource efficiency, minimized harmful impacts, maximized economic value creation, and maximized economic value retention. Though implications to society were not a commonly identified attribute in literature, the economic and environmental benefits brought about by CPs can lead to advantages for society. Therefore, societal benefits and implications are included as an attribute in this PCA framework. These attributes were shared with consumer electronics industry stakeholders through a workshop for verification and validation. All the attributes were confirmed as important to evaluating product circularity.
Next, a comprehensive examination of scientific literature and industry reports was carried out to identify indicators for each attribute and define metrics to assess each indicator. Because indicators as well as metrics can be very industry- and even product-specific, the definition of indicators and metrics was conducted with a focus on CEPs. Often organizational size (e.g., small vs. large companies) as well as resources can limit data availability; thus, the work focused on defining example metrics for each indicator as a guide for industry stakeholders to subsequently adapt them depending on the specific use case and data availability.

Table 1. Key attributes of circular products*.

Drivers and Enablers	Outcomes: Circular Products	Benefits and Implications
Effective resources selection [18]	Incorporate value recovery strategies [20]	Optimized resources efficiency [23]
(Re) Design to facilitate circular characteristics [4]	Extended product use-life [21]	Minimized harmful environmental impacts [14]
Stakeholder consideration and engagement [19]	Incorporate closed-loop resources flow [22]	Maximized economic value creation [19]
	Facilitate multiple lifecycles [16]	Maximized economic value retention [17]
	Minimize waste [21]	Increased societal benefits

** Based on a comprehensive review supported by several other sources which are not shown due to lack of space.*

In total 29 indicators and 79 example metrics were developed. Fig. 5 exemplifies one attribute with indicators and example metrics. The attribute ‘effective resources selection’ represents the emphasis on minimizing or eliminating virgin resources during CPD. Thus, alternative resources, such as recycled, upcycled, biodegradable, durable and safe (non-hazardous and non-toxic) materials, as well as recyclable and renewable resources, should be prioritized [18, 23]. Indicators such as material utilization, recovered material usage, and energy usage can be used to convey the extent to which resources are being selected effectively. They can be quantitatively measured using metrics such as the % of virgin material used, % of recycled materials, or the rate of non-renewable energy utilization.

The same approach was followed for the other attributes to identify indicators and metrics. The indicators are further verified through one-on-one meetings with experts from various consumer electronics companies to verify their relevance to evaluating the different attributes. The attributes are also being further verified during these meetings.

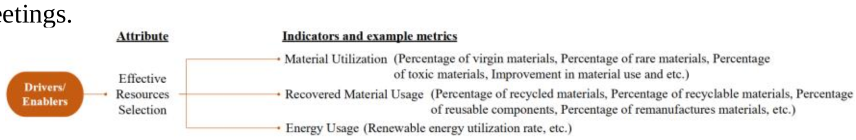

Fig. 4. Example of indicators and metrics for a circular product attribute.

6 Conclusions and Future Work

The successful operationalization of CE requires a comprehensive focus across the lifecycle—on product design, manufacturing, use, and EoL management—to establish seamless circular flow of resources. The cornerstone of this endeavor lies in the development of CPs which will be a catalyst for creating sustainable products, eventually enabling sustainable value creation for all stakeholders. One of the pre-requisites for designing CP is the ability to comprehensively evaluate products to assess the extent to which they satisfy circularity requirements. This paper presents a comprehensive approach founded upon a systems-based framework that integrates key attributes, indicators, and metrics for PCA. Industry experts from the consumer electronics sector have been continuously engaged in developing the method to ensure the usefulness and industry-relevance of the work. Future work will focus on implementing the systems-based framework for PCA to validate its effectiveness. Case studies will be conducted to assess the circularity of different products, starting with the consumer electronics sector. Further improvements will be made to facilitate a more effective design of CPs. Examining effective implementation by industry experts and striving for a practical PCA despite data limitations are imperative for tangible progress towards a CE and a sustainable future.

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