TRANSITIONING TOWARDS CIRCULAR CONSUMER ELECTRONICS PRODUCTS

Junwon Ko[1], **Gisele Bortolaz Guedes**[1] **Fazleena Badurdeen** [1] **I.S. Jawahir** [1]
KC Morris[2], **Vincenzo Ferrero**[2]

[1] Institute for Sustainable Manufacturing (ISM) and Department of Mechanical & Aerospace Engineering,
University of Kentucky, Lexington, KY, USA
[2] National Institute of Standards and Technology, Gaithersburg, MD, USA

ABSTRACT

In the present digital era, consumer electronics have become ubiquitous, providing numerous conveniences in various aspects of daily life. However, the significant increase in the production and use of consumer electronics products coupled with the unplanned end-of-life management leads to the depletion of rare earth materials, increasing carbon emissions, and growing electronic waste, thus presenting unique sustainability challenges. Numerous studies have emphasized the development of circular electronic products that align with Circular Economy principles to address these issues. Consumer electronics industry-led initiatives, such as the Circular Electronics Partnership (CEP), have also made a concerted effort to establish key requirements to ensure the circular flow of consumer electronics. However, the broadness of these requirements poses challenges in operationalizing them to facilitate more effective decision-making during product design. This paper addresses this gap by proposing more specific and actionable circular product attributes identified and compiled from extant literature. The relevancy of these attributes was verified in consultation with industry practitioners. These attributes were then mapped to the broad, generic requirements proposed by the CEP. By doing so, this research contributes to translating the CEP-proposed requirements into more specific and actionable attributes to facilitate the design and manufacturing of circular products in the consumer electronics industry.

Keywords: Circular Economy; Circular Product; Product design; Consumer electronics

1. INTRODUCTION

In recent years, Circular Economy (CE) has been evolving from a theoretical model toward a tangible practice that seeks economic growth and minimizes harmful impacts on the environment while meeting the needs of a growing population. Its essence is rooted in the restoration and regeneration of products and materials at end-of-life (EoL) [1]. In a CE, the value of products and materials is maintained at the highest level for as long as possible through restoration processes such as reuse, remanufacture, and recycling, forming a closed-loop system that optimizes resource use and minimizes waste. Regeneration, on the other hand, specifically targets food and biodegradable materials, promoting processes that return these elements back to the Earth. Regeneration aims to emulate natural cycles, ensuring that waste is not just minimized but actively contributes to regenerating nature.

The growing concerns over resource scarcity, environmental degradation, and the unsustainable generation of waste underscore the urgent need to adopt CE practices. The consumer electronics industry, in particular, is at a pivotal moment. Despite its significant contributions to advancements and conveniences in various aspects of daily life, it has also accelerated resource depletion, increased carbon emissions, and caused a surge in electronic waste, or e-waste. Global E-waste Monitor reported that 44.7 million metric tons of e-waste were generated in 2017 [2]. From 2010 to 2019, e-waste generation increased by 60 percent and is projected to reach 75 million metric tons by 2030 [3]. Yet, only 20 percent of e-waste was properly collected and recycled in 2018 [4]. It was also found that the increase in e-waste generation was approximately five times greater than the increase in properly managed e-waste from 2014 to 2019 [5]. Such statistics highlight a significant shortfall in the consumer electronics sector and emphasize the necessity for immediate and innovative solutions.

The concepts of CE offer a viable solution to address these challenges. By maintaining the continuous use of products and materials, significant reductions in carbon emissions can be achieved, e-waste can be reduced, and supply chain pressures can be alleviated. Moreover, this shift does not just provide environmental benefits; it presents a substantial economic opportunity. The material value of the world's e-waste stands at a staggering $57 billion, surpassing the Gross Domestic Product (GDP) of many nations [5]. Businesses can harness this potential by embracing innovative circular business strategies and optimizing the entire lifecycle of their products. At the heart of the transformation towards CE is the product-level transition, which focuses on designing, manufacturing, using, and managing EoL products in alignment with CE principles. This change is pivotal, as it sets the foundation for broader, systemic shifts at industrial and national levels [6].

Several prior academic studies have investigated the requirements for a product to be considered circular ([4], [7], [8]). Most, however, focus on limited aspects and lack substantial engagement with industry stakeholders, making their findings less applicable in real-world scenarios. Meanwhile, six leading global non-profit organizations and the International Telecommunication Union initiated the alliance called Circular Electronic Partnership (CEP) to promote the product-level transition toward a CE in the consumer electronics sector. This coalition united major industry stakeholders from the technology, consumer goods, and recycling sectors, and proposed the requirements for circular consumer electronics.[9]. These CEP-proposed requirements, while beneficial, tend to be broad and generic, posing challenges to effectively operationalizing them. Hence, this paper aims to identify specific, actionable attributes that characterize circular consumer electronics, facilitating more effective and practical decision-making for circular product design (CPD). The paper is organized as follows: Section 2 discusses the background, research methodology, literature review, and preliminary results; Section 3 presents 13 key CP attributes based on the synthesis of the findings from Section 2, demonstrates the mapping between these attributes and the CEP-proposed requirements, and highlights the broader impacts of this paper; Section 4 concludes the paper with key takeaways and a discussion of future work.

2. MATERIALS AND METHODS

This section discusses the requirements for circular consumer electronics proposed by the CEP [9] and the approach the authors followed to address the challenges in operationalizing these requirements by identifying more specific CP attributes. Additionally, a review of related work and preliminary results are presented.

2.1 Background

Diverse stakeholders from the consumer electronics industry have united through the CEP initiative to foster a collective shift towards CE and proposed three pivotal requirements essential for circular consumer electronics [9]. These requirements are illustrated in Figure 1.

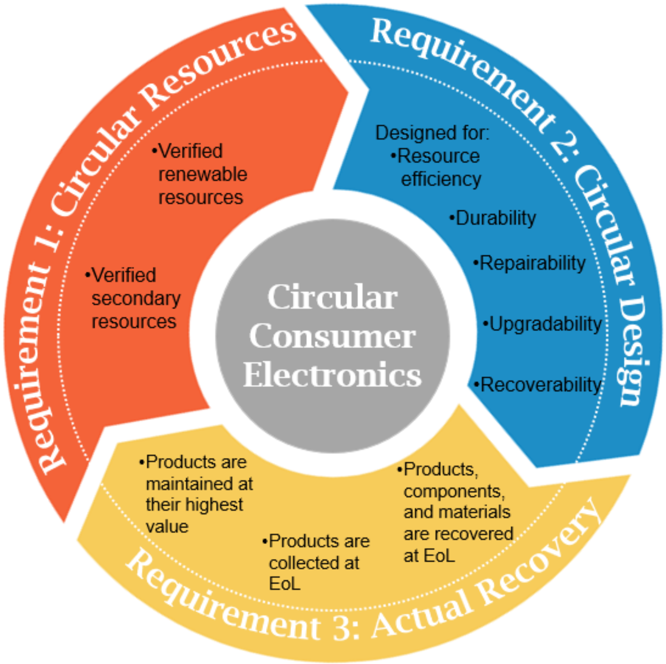

FIGURE 1: KEY REQUIREMENTS FOR CIRCULAR CONSUMER ELECTRONICS, ADOPTED FROM CEP [9]

Requirement 1: Circular Resources

A circular electronic product is comprised of secondary and renewable resources with verified characteristics. Secondary resources refer to those that have been previously utilized, such as components and materials that have been refurbished, remanufactured, or recycled. Renewable resources, on the other hand, are those that nature can replenish at a pace equal to or faster than they are consumed. For these secondary and renewable resources to qualify as genuinely circular, the ability to trace and confirm vital information, including the entire history of custody, is crucial. This is particularly true for secondary resources, where the complexity of their pathways requires robust verification. Though agreed-upon tools and techniques for verification are yet to be established, it is essential to confirm that these components and materials are, indeed, secondary. This means having clear, transparent records of their origins, the facilities where they were recovered, the countries where they were processed, and detailed information about the environmental, health, and safety standards followed during recovery processes. The CEP also emphasizes transparency and verification of renewable resources to ensure that these resources are not just renewable but also produced in an environmentally responsible manner. All these aspects are embodied in the first requirement of “Circular Resources.”

Requirement 2: Circular Design

Secondly, CEP identifies design characteristics that enable circularity. These include design for resource efficiency, durability, repairability, upgradability, and recoverability.

- **Resource efficiency:** The design for resource efficiency indicates minimizing resource use during manufacturing while ensuring the product operates with maximum resource efficiency throughout the product use phase. For most electronic products, this primarily relates to energy efficiency. Where applicable, such designs also aim to reduce consumables, exemplified by printers designed to use the least amount of ink necessary for the desired print quality.
- **Durability:** The lifespan is significantly extended by focusing on the durability of both the product and the materials used. Such designs ensure the product's functional robustness and maintain its aesthetic endurance over time. For instance, using scratch-resistant materials to protect screens from minor damage focuses on enhancing durability by ultimately contributing to less frequent product replacements.
- **Repairability:** Durable designs can still be prone to wear and tear, which makes designing for repairability essential for a circular electronic product. Design for repairability ensures that the repair process is easy and efficient in case the product is rendered inoperable, thereby maximizing the product’s usable life. The key to this approach is the ability to easily disassemble products, achieved through a simple, modular, and standardized design.

- **Upgradability:** Designing to allow for upgrades, both in appearance and function, to satisfy evolving consumer preferences and needs is imperative. Depending on the device, these upgrades can take the form of physical changes or software updates. Modular designs, for example, make it possible to easily switch out parts, like replacing a laptop's hard drive to accommodate a user's additional storage needs, without buying an entirely new laptop. For software, regular updates to bring new features or improve existing ones can sustain a consumer's interest in continuing to use their device for extended periods, reducing the necessity of purchasing a new product.
- **Recoverability:** For a consumer electronic product to be truly circular, its design must be optimized to facilitate recovery of the remaining value through effective and efficient EoL processing. Ease of product disassembly supports easy removal of components and parts without causing destructive damage, thus preserving the potential for refurbishment or remanufacturing. Moreover, the materials used in a circular electronic product must be recyclable, which means no inclusion of hazardous substances that could hinder or entirely preclude the recycling process.

Requirement 3: Actual Recovery

Though a product may have been designed with those CEP-proposed circular design criteria in mind, the optimization of the product's use phase, EoL collection, and actual recovery processes will determine the product's operation in a closed-loop. These aspects are described in the third requirement: "Actual Recovery." For a circular electronic product to maintain maximum utility and value during the use phase it may require monitoring its usage and relevant maintenance. Product monitoring can reveal insights into product usage patterns, current state, and potential lifespan. Leveraging such data, a company can provide regular maintenance services to prevent early component wear and tear or repair services as needed. Ongoing software updates and support are also crucial for preserving the functionality and security of a circular electronic product. Additionally, when consumers no longer want products that are still functioning, guidance must be given on how to resell them such as via peer-to-peer networks, the original equipment manufacturers (OEM), retailers, or firms specialized in resale.

When a product reaches EoL (for example, due to obsolescence or breakdown), it must be collected to initiate value recovery. An effort to recover all materials of a circular electronic product begins upon its EoL collection. This recovery happens either at the level of components or materials. In the former approach, once the product is disassembled, its components and parts are reused in similar products or for entirely different uses. Such a process often involves refurbishing or remanufacturing the components, as well as clearing any stored data. Material-level recovery through recycling is pursued when reusing components is not feasible to preserve as much of the original value as possible. Recyclers must strive to minimize the downcycling of these materials. Figure 2 depicts the journey of a circular electronic product from material production to post-use recovery, further emphasizing the importance of actual recovery processes as they add significant value back to the pre-use stage. Thus, the third requirement embodies all the capabilities discussed above, necessary to facilitate the recovery activities.

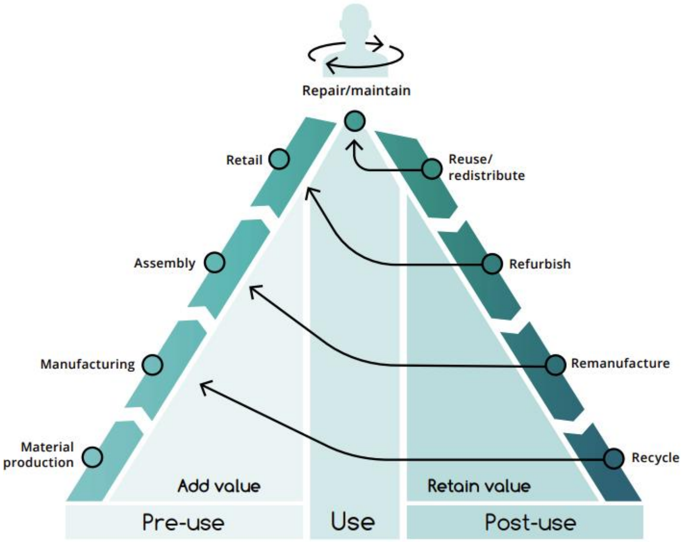

FIGURE 2: LIFECYCLE VALUE RETENTION IN CIRCULAR ECONOMY, ADOPTED FROM THE CEP [9]

The requirements proposed by the CEP outline the fundamental criteria that consumer electronics must meet to be considered circular. However, their broadness poses challenges in operationalizing them effectively and assessing the extent to which they are satisfied. To address this gap, the authors identified more concrete and actionable attributes that characterize CPs, through a university-industry-government collaborative effort led by the National Institute of Standards and Technology (NIST).

2.2 Methodology

The methodology employed in this research is shown in Figure 3. The first step involved reviewing the related work, focusing exclusively on publications pertinent to CE principles, Circular Product Design (CPD), and product circularity. Based on the review of related work, an initial set of CP attributes was identified. These preliminary attributes were then subjected to feedback from industry experts through a workshop, leading to their revisions. Further refinement was achieved through one-on-one meetings with industry experts, ensuring detailed and specific feedback. This iterative process led to the identification of core attributes that describe features/properties of CP. Finally, these core attributes were mapped to the CEP-proposed requirements discussed previously based on their interrelationships. This analysis enables translating these generic and broad requirements into more specific and actionable decision criteria in CPD, thereby contributing to the design and production of CPs in the consumer electronics sector.

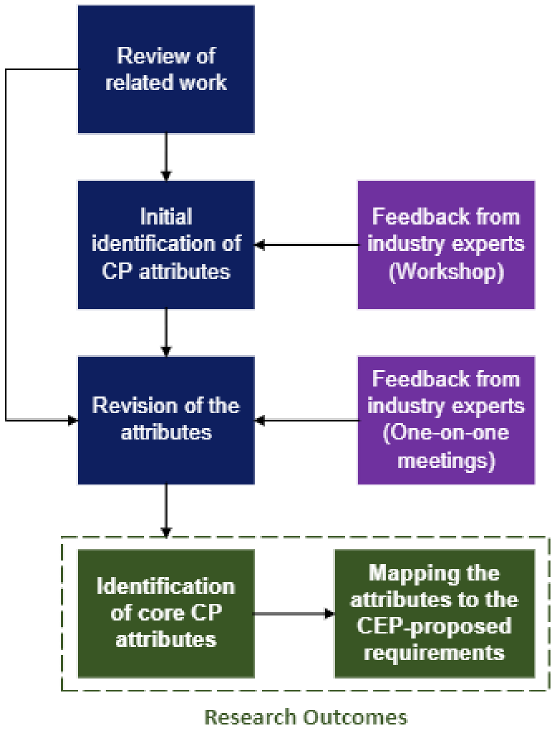

FIGURE 3. RESEARCH METHODOLOGY

2.3 Literature Review

A focused literature review was conducted to identify attributes of CP. Given the lack of a concrete definition of CE [6], understanding its fundamental principles is essential. Therefore, literature on the CE concept, as well as on CPD and product circularity assessment, was reviewed to identify key elements that must be incorporated into CPs. Specific keywords, such as product-level CE, closed-loop product design, and CP characteristics, were strategically used to compile relevant literature. These keywords were selected to ensure that all gathered materials closely aligned with the scope of this paper. Additionally, relevant references cited in the initially identified papers were thoroughly examined to trace the origins of the information, verify its reliability, and deepen the understanding of CP by exploring these foundational sources.

The conceptualization of CE has been influenced by various schools of thought such as industrial ecology, regenerative design, and biomimicry ([1], [10], [11], [12]). These schools of thought emphasize the circular flow of resources for both environmental and economic benefits. The Ellen MacArthur Foundation (EMF) has played a key role in raising awareness about CE, describing it as an industrial system designed to be restorative and regenerative [1]. According to the EMF, the principles of CE involve minimizing waste and pollution, regenerating natural systems, and circulating materials and products to maintain their highest value [13]. A recent study by Kirchherr et al. reviewed 221 definitions of CE and highlighted value recovery strategies such as redesign, recovery, reuse, remanufacturing, and recycling as core CE principles [14]. They also emphasized the systems perspective of CE, including its application at micro (product, firms, consumers), meso (industrial parks), and macro (city, region, nation, global) levels, and its benefits for the environment, economy, and society [14]. In summary, common CE principles in relevant literature include regeneration, value recovery strategies that facilitate restoration, application across different operational levels, and economic as well as environmental benefits.

Various studies focusing on the discussion of CPD were also reviewed to identify design characteristics that must be incorporated into CP. Van der Berg and Bakker [15] presented a product design framework for CE, describing CP development as the creation of products that can re-enter their lifecycles multiple times while minimizing harmful environmental impact. They also underscored the significance of multiple product lifecycles and the associated environmental benefits. Circular Tayside, a collaborative group advocating for CE adoption in local businesses and organizations, emphasized that CP utilizes minimal or no virgin resources and the importance of EoL considerations in CPD [16]. Bressanelli et al. [17] explored the implementation of CE to mitigate waste in the electrical and electronic equipment industry. Their study highlighted the need to consider various stakeholders in the design process to achieve CP. They also identified significant economic and environmental benefits from closing the loop for products, components, and materials, highlighting these as potential advantages of CP. In a similar vein, Institutional Shareholder Services emphasized the importance of closing the product lifecycle loop and considering the next lifecycle during the initial CP design phase [18]. Lastly, Suppipat and Hu [4] reviewed circularity design tools in the electrical and electronics industry, presenting sixteen product design concepts derived from seven circularity design characteristics of business models. These concepts were categorized into three groups: societal (e.g., collaborative community design, scalable design, customization), emotional (e.g., classic design, design for attachment and trust, design for reliability), and physical (e.g., modular design, design for durability, etc.).

The growing awareness of CE and CP led to numerous publications exploring the assessment of product circularity. Linder et al. [19] proposed a metric for measuring product circularity, emphasizing the importance of reuse, remanufacture, and recycling to establish closed-loop materials and components. Similarly, Cayzer et al. [20] presented indicators to assess product performance in CE, which cover manufacturing, use, and EoL stages. This suggests that the total lifecycle stages, from pre-manufacturing to EoL, must be considered in the design process for CP. Expanding on this, Conte and Brogna [21] developed a methodology to evaluate product circularity. In their study, novel design, technological innovation, materials management, and customer involvement were identified as key catalysts for improving product circularity. More recently, Hansen and Revellio [22] emphasized extending product lifespan and coordinating with multiple stakeholders to enhance product circularity. Vimal et al. [23] introduced a framework for measuring circularity, stressing the importance of considering all lifecycle stages in the circularity assessment. They also underscored how CP can lead to reduced environmental impacts by enabling multiple lifecycles for products.

The findings from the literature review were carefully analyzed and consolidated to identify preliminary attributes of CP. These were then assessed through Pareto analysis to identify and prioritize the 20% of attributes that account for 80% of the CP characteristics. Due to page limitations, more detailed information about the literature review process and the Pareto analysis results cannot be presented here. They can be found in Guedes et al. [24] and Ko et al. [25].

2.4 Industry Stakeholders Engagement

Industry practitioners, such as product designers, supply chain managers, and sustainability specialists, are crucial stakeholders in facilitating the transition toward product-level CE [14]. However, many academic studies presenting CP attributes lack engagement with these industry stakeholders, rendering their findings less applicable to real-world scenarios. To address this gap, an initial set of CP attributes identified through a focused literature review and Pareto analysis (described previously) was shared with 20+ industry practitioners through a virtual workshop and one-on-one meetings held by the University of Kentucky. These practitioners were from global consumer electronics companies, including some Fortune 500 companies, with roles ranging from Environmental Affairs Professional to Principal Sustainability Program Manager, Sustainable Materials Innovation Lead, and Corporate Circularity Lead. During the workshop, the initial set of CP attributes was presented to the participants, and their feedback was collected through a survey. The survey assessed the relevance of each attribute in terms of accurately describing features/properties of CP and their applicability in real-world scenarios. Following the workshop, one-on-one meetings were conducted with multiple global consumer electronics companies to engage in more in-depth discussions about the attributes. This collaborative approach ensured that the CP attributes were verified and refined with direct input from industry stakeholders, enhancing their practical relevance and applicability.

3. RESULTS AND DISCUSSION

Table 1 presents the thirteen key industry-verified attributes of CPs identified through the university-industry-government collaboration and classified into three distinct categories: Driver and Enablers, Outcomes, and Benefits and Implications. This section explores these attributes in detail, noting that they are specifically described in the context of a circular electronic product. These attributes were then mapped to the CEP-proposed requirements for circular electronic products described in the Background section. This analysis is pivotal for converting the broad CEP-proposed requirements into more specific and implementable elements for the design and production of circular consumer electronics.

3.1 Drivers and Enablers

The prerequisites for developing a circular electronic product are termed ‘drivers and enablers’ and classified into three subcategories, as described below.

- **Effective resource selection:** As elaborated by Ellen Macarthur Foundation [1], Saidani and Kim [26], and Nag et al. [27], this attribute refers to the strategic choice of resources utilized throughout a product’s entire lifecycle, encompassing its design, manufacturing, delivery (including packaging and transportation), usage, and post-use phases. Preferred resources include recycled, recyclable, biodegradable, durable, and safe (nonhazardous and non-toxic) materials, as well as recyclable and renewable resources. The production of these resources must be sustainable to ensure that the solutions do not create more significant problems than those they are designed to solve.

TABLE 1. KEY INDUSTRY-VERIFIED ATTRIBUTES OF CIRCULAR PRODUCTS

Category	CP Attributes
Drivers and Enablers	• Effective resource selection • (Re) Design to facilitate circular characteristics • Stakeholder consideration and engagement
Outcomes: Circular Products	• Incorporate value recovery strategies • Product use-life extension • Incorporate closed-loop resource flow • Facilitate multiple lifecycles • Minimize waste
Benefits and Implications	• Optimized resource efficiency • Minimized harmful environmental impacts • Maximized economic value creation • Maximized economic value retention • Societal benefits and implications

- **(Re-)Design to facilitate circular characteristics:** A circular electronic product must not only be resource-efficient but also be designed to ensure the product’s longevity and continuous flow of its materials ([15], [17], [22]). This involves, for instance, designing for modularity and component standardization to allow easy, safe disassembly as well as maintenance and repair. The product should also be designed for upgradability and durability to increase its lifespan. Furthermore, it must be designed with recovery, reuse, remanufacture, and recycling in mind to sustain its maximum utility and value. This comprehensive design approach ensures the product’s extended use and multiple lifecycles.

- **Stakeholder consideration and engagement**: The successful development of a circular electronic product begins with the active participation and collaboration of various stakeholders, such as manufacturers, suppliers, consumers, potential EoL service providers, and policymakers ([21], [27], [28],). Their collective engagement is essential in ensuring transparency and the sharing of information regarding the resources used for effective resource selection. Considering and engaging various stakeholders during the design phase is also crucial since they significantly contribute to facilitating value recovery, particularly during post-use.

3.2 Outcomes: Circular Products

Drivers and enablers lead to circular electronic products, which possess the following characteristics:

- **Incorporate closed-loop resource flow**: This attribute indicates that a circular electronic product is made of resources that are not sourced exclusively from virgin resources, creating a closed-loop flow of materials aiming to mimic nature where nothing goes to waste ([28], [29], [30]). Such a flow not only helps in conserving resources but can also significantly reduce pollution and the energy demands typically associated with the extraction and processing of raw materials, as well as the disposal of waste ([9], [31]).
- **Product use-life extension:** A circular electronic product is characterized by a prolonged functional lifespan, achieved through strategic resource selection and designed with focus on durability to increase use-life, modularity to ease maintenance and repair, and upgradability to prevent obsolescence ([30], [32], [33]). This extended use-life primarily lowers the frequency of replacing a product, ultimately leading to the reduction of waste generation and resource depletion ([34], [35]).
- **Incorporate value recovery strategies**: This attribute signifies that when a circular electronic product reaches the end of its initial life cycle, its value must be restored as much as possible through value recovery strategies of recover, reuse, remanufacture, and recycle ([22], [27], [36]). Recover entails collecting, sorting, and cleaning products, as well as possible disassembly into components. When reuse (through direct reuse of product, reuse of product after refurbishment or reuse of components) and remanufacture no longer offer practical benefits, where the efforts and resources necessary do not justify the outcomes, the components are further disassembled for recycling and use as secondary materials.
- **Facilitate multiple lifecycles**: Through the implementation of value recovery strategies, a circular electronic product, or at the very least its components or materials, serves multiple lifecycles, within the same or different applications ([4], [23], [37]). This attribute ensures that each element of the product is utilized to its fullest potential.
- **Minimize waste**: A circular electronic product with the above characteristics minimizes the quantity of waste generated during its entire lifecycle ([27], [33], [38]).

3.3 Benefits and Implications

These attributes reflect desired benefits and implications to be avoided through circular electronic products.

- **Optimized resource efficiency**: In a circular electronic product, resources are utilized to their fullest potential through strategic selection, effective use, and recovery ([27], [23], [30]).
- **Minimized harmful environmental impacts**: A circular electronic product minimizes the impacts on the environment ([17], [30]). The efficient use of resources, extended product use-life, and the recovery of values all contribute to this by reducing pollution, greenhouse gas emissions, and the adverse effects of raw material extraction, manufacturing, and waste disposal.
- **Maximized economic value creation**: By utilizing resources to their maximum potential, costs in material procurement and waste management can be significantly saved ([22], [39]). Value recovery strategies, such as reuse and remanufacture, also stimulate new business models and revenue streams, thereby fostering economic value creation.
- **Maximized economic value retention**: A circular electronic product where its utility, or that of its components and materials, is maintained for as long as possible through value recovery strategies can lead to maximizing economic value retention ([4], [8], [19]). This provides economic benefits and encourages a shift in consumption patterns towards more sustainable practices.
- **Societal benefits and implications**: Developing a circular electronic product brings numerous benefits to consumers, manufacturers, and society at large ([40], [41], [42]). Consumers can benefit from the longer product lifespans with reduced need for frequent replacements. Meanwhile, manufacturers can enhance brand image and consumer loyalty in an increasingly environmentally conscious market. On a broader societal level, reducing pollution and emissions significantly contributes to improving health and safety. New job opportunities can also be created in fields such as repair, maintenance, and sectors related to reuse, remanufacturing, as well as recycling.

3.4 Mapping Attributes to CEP-Proposed Requirements

A closer analysis and the discussion above reveal that the work done by the CEP is connected, either directly or indirectly, to the attributes in the "Drivers and Enablers" and "Outcomes: Circular Products" categories, identified through the current project and presented in this paper. Space limitations of this paper preclude a detailed elaboration of these interrelationships, which are instead depicted in Figure 4. For example, the CEP-proposed requirement "Circular Resources" emphasizing the use of secondary and renewable resources, directly corresponds to the attribute "Effective Resource Selection," which emphasizes the strategic selection and utilization of input resources throughout the product's life cycle (e.g., recycled, recyclable, biodegradable, durable materials, etc.). Indirect correspondence between a CEP-proposed requirement and an attribute suggests that one either supports or results from the other. In this context, "Circular Resources" is facilitated by "Stakeholder Consideration and Engagement," which underscores the need for active collaboration among stakeholders for transparent resource information sharing. "Circular Resources" also serves as a foundation for enabling the attributes in the "Outcomes: Circular Products" category. As an example, utilizing secondary resources is vital for moving towards a closed-loop system and facilitating multiple lifecycles. The mapping further demonstrates the interrelationships between categories, showing that the attributes in the "Drivers and Enablers" group lead to the CP characteristics outlined in "Outcomes: Circular Products," all of which collectively contribute to realizing the benefits listed in the "Benefits and Implications" category. This analysis aims to translate the broad, generic requirements proposed by the CEP into more specific and actionable decisions for designing, manufacturing, and assessing circular consumer electronics to steer the industry toward a more sustainable future.

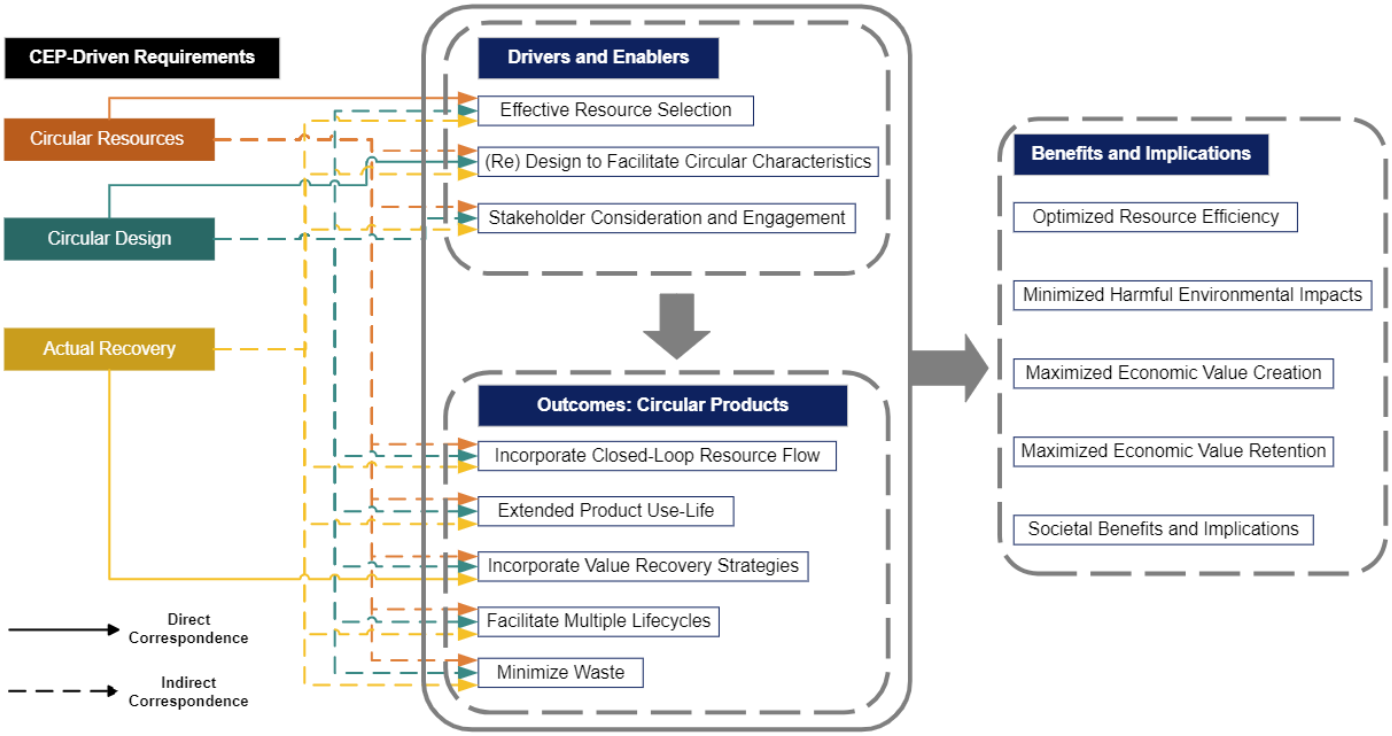

FIGURE 4. MAPPING BETWEEN THE CEP-DRIVEN REQUIREMENTS AND THE INDUSTRY-VERIFIED ATTRIBUTE

3.5 Discussion

As previously highlighted, shifting industrial systems towards CE is imperative to overcome the limitations of current linear practices. Such a shift begins with the micro-level transition where products must be designed, manufactured, used, and managed at EoL following the principles of CE. A foundational step in this journey involves identifying what makes a product circular. The work proposed by the CEP plays a pivotal role in this step by establishing three core requirements for consumer electronics to be considered circular. Although these requirements align with CE principles, their broadness presents challenges in measuring their impacts, evaluating their fulfillment, and verifying that they have achieved their objectives. Precise measurement is essential for operationalizing these requirements because it provides concrete targets and benchmarks for companies to aim for in their products. Without clear, measurable goals, the application of CE principles in products risks remaining theoretical rather than practical, impeding effective adoption in the industry. Therefore, comprehensive capabilities to measure and assess product circularity are crucial in enabling a genuine transition towards micro-level CE.

Various methods have been proposed for assessing circularity, as outlined by Oliveria et al. [42], Saidani et al. [43], and Lindgreen et al. [44]. Nevertheless, Ko et al. [25] reveal some common limitations in these methods, such as the variability of criteria in each method, a lack of sector-specific approach, and low industry adoption due to insufficient engagement with industry stakeholders. These limitations underscore a need for more comprehensive and practical methods to assess product circularity. Developing such a method requires the identification of CP attributes, indicators that describe these attributes, and relevant metrics for measuring such indicators. This paper contributes to achieving these needs by identifying a set of specific attributes characterizing CPs, derived from extant literature review, and verified through stakeholders in the consumer electronics industry. These key industry-driven attributes clarify what constitutes CPs, including their drivers, characteristics, and broader impacts. They also lay the groundwork for developing a comprehensive suite of indicators and metrics, leading to an effective method for assessing product circularity.

The mapping between these CP attributes and the CEP-proposed requirements for circular consumer electronics shows that each requirement can be translated into more specific and actionable items. It also demonstrates a consensus between academic findings and industry needs, with each CEP requirement connected to relevant attributes, either directly or indirectly. Therefore, the work presented in this paper facilitates the transition from broad, conceptual CE principles to precise, actionable decisions, thereby enabling consumer electronics companies to not only understand but actively implement such principles in their products. However, it must be noted that these attributes cannot be used in the absence of contextualization to account for variability in the system of operation. For example, concerns such as the availability of suitable secondary-resource streams, recovery and recycling methods, and trade-off evaluation with use-phase resource consumption should factor into the circular design process as well.

4. CONCLUSIONS & FUTURE WORK

This paper presents and thoroughly explains thirteen key attributes characterizing CPs, identified through a university-industry-government collaborative effort. These attributes were verified through engagements with experts in the consumer electronics industry, ensuring their relevance and applicability. Through this collaborative research, this paper elucidates the foundational principles of CPs and establishes a clear understanding of what drives CPs, their distinctive characteristics, and consequent impacts. Given the inherent complexity of products and the vast diversity of product types, the authors acknowledge exceptions and underscore the need for conducting trade-off analyses to ensure desirable outcomes. The thirteen attributes were then linked to the requirements for consumer electronics to be considered circular, set by the CEP, offering a guide for converting these requirements into specific, actionable steps. Hence, the paper also contributes to translating theoretical concepts of CE and CP into more practical applications and actualizing the integration of circular design and manufacturing principles in the industry.

Future work will focus on the identification of indicators and metrics corresponding to the key industry-verified attributes of CPs, proposed in this paper. These indicators and metrics will serve as precise measures for the evaluation of each attribute. The ultimate goal is to develop a comprehensive method for assessing product circularity, enabling manufacturers and designers to quantitatively gauge their products' circularity. Once this comprehensive method is developed, case studies will be conducted using actual products to measure their circularity using the developed method. This will provide practical validation and demonstrate the method's effectiveness in real-world applications.

Additionally, the paper's authors are actively participating in ASTM International's Work Item on "New Guide for Principles for Circular Product Design" [45] to standardize CPD principles. The establishment of standardized CPD principles with a robust method for assessing product circularity will also play a vital role in facilitating an industrial shift towards CE at all levels.

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