REVIEW PAPER

Nexus Between Life Cycle Assessment, Circularity, and Sustainability Indicators—Part I: a Review

Michael Saidani[1] · Harrison Kim[1]

Abstract

Circular economy (CE) and sustainable development are not systematically synonyms and some trade-offs might occur between circularity and sustainability. This study addresses the nexus—i.e., the potential concurrence, complementarity, or conflict—between circularity and sustainability indicators to develop and monitor more circular and sustainable systems, using two complementary research approaches: (i) a review and comparison of existing works covering circularity and sustainability performances concurrently (Part I), (ii) new experimentations on more circularity and sustainability to fill the gaps of previous works and bring more concrete insights for practitioners on this matter (Part II). In the present Part I, we provide a state-of-the-art summary of the solutions and challenges related to the measurement of the sustainability performance of CE strategies. The contributions and limitations of life cycle assessment (LCA), leading sustainability, and circularity indicator–based approaches are analyzed, compared, and illustrated. Ten independent studies experimenting and comparing LCA and circularity indicators on different products are analyzed and compared. Depending on the product context and the CE scenarios evaluated, several types of connections emerged: beneficial, conditional, or scenario-dependent trade-offs. To fill the gaps of the existing studies exposed at the end of this paper (Part I), a new set of experimentations is designed and conducted (Part II) to further understand how these different approaches and indicators could be appropriately deployed to develop more circular and sustainable product systems.

Keywords Circular economy · Circularity indicators · Sustainability performance · Interconnection · Literature survey · Case studies · Comparative analysis

Introduction

While the momentum around the circular economy (CE) transition is still vivid and a significant driver for more sustainable practices in the industry [1], the proper assessment and deployment of CE initiatives and strategies are of utmost importance. A CE

✉ Michael Saidani
  msaidani@illinois.edu

1   Department of Industrial and Enterprise Systems Engineering, University of Illinois at Urbana, Champaign, IL, USA

🖉 Springer

model can be seen as a model of production and consumption of goods through closed-loop material flows, internalizing environmental externalities linked to the extraction of virgin resources, the generation of waste, and pollution [2]. On the one hand, moving towards more CE practices is increasingly acknowledged to contribute to the sustainable development goals (SDGs) [3, 4], notably in terms of responsible consumption and production (SDG12). On the other hand, CE and sustainable development are not systematically synonyms. Some trade-offs might occur between circularity and sustainability indicators—a.k.a. triple bottle line (TBL) indicators. In other words, circularity does not intrinsically ensure better social, economic, and environmental performance, i.e., sustainability.

To effectively monitor the CE transition, its performance measurement is crucial [3]. The sustainability of CE strategies needs to be measured against their linear counterparts to identify and avoid strategies that increase circularity but lead to unintended externalities [5]. For instance, the application of CE principles would encourage recycling to incineration, while energy recovery through incineration could sometimes be more beneficial from an environmental perspective [6] when performing a life cycle assessment (LCA). More generally, CE principles such as recycling, remanufacturing, or high-durability manufacturing are processes that usually require relatively high energy inputs and generate variable ecological outputs [7]. Synthetizing the main findings of 38 previous systematic literature reviews related to the circular economy, Sehnem et al. (2021) highlighted the low maturity of CE-related research and the limited dissemination of CE practices [8]. As an important area for future research, the authors stated that the benefits arising from the adoption of CE from the perspective of sustainability should be further quantified and discussed. In fact, rather than generically assuming positive impacts in regard to the SDGs, researchers should focus on interdependencies and trade-offs between circularity and SDGs targets [8].

As a matter of fact, the connection between circularity scores and sustainability performances needs to be further investigated. While the proliferation of circularity indicators has received considerable attention, there is still a lack of critical review on the combinations of methods that specifically quantify the sustainability impacts of CE strategies [5]. To Korhonen et al. (2018), scientific research is needed to secure that the actual environmental impacts of CE work towards sustainability [9]. To Harris et al. (2021), the implementation of CE models is to improve the environmental performance of society, and CE initiatives must be based on evidence and quantification to avoid promoting "circularity for circularity's sake" when it does not contribute to environmental resilience [10]. In this line, the present study addresses the nexus (i.e., the link, concurrence, complementarity, and/or conflict) between circularity indicators (c-indicators) and sustainability indicators (s-indicators) to develop and monitor more circular and sustainable systems, using two complementary research approaches: (i) a review and comparison of existing works covering circularity and sustainability performances simultaneously (Part I), (ii) new experimentations on more circularity and sustainability to fill the gaps of previous works and bring more tangible insights for practitioners on this matter (Part II). In Part I, the research methodology is presented, and the main life cycle-, sustainability-, and circularity-based measurement approaches are first reviewed (see the "Materials and Methods" section). Then, ten studies applying both LCA and circularity indicators are further analyzed and compared in order to discuss the potential alignment and trade-offs between sustainability and circularity performances (see the "Results" section). Eventually, elaborations on the current contributions and limitations of the existing literature are made (see the "Discussion and Perspectives" section), before opening up to the Part II of this research work.

Materials and Methods

In the following, we unfold a state-of-the-art summary of the solutions and challenges related to the measurement of the sustainability performance of CE strategies. By solutions, we mean here any approaches, including tools, methods, and indicators, intended to assess one or several sustainability-related aspects of CE initiatives. First, in the next sub-sections, life cycle-, sustainability-, and circularity-based indicators are further introduced. Then, to identify the studies which apply both LCA and circularity-based approaches on the same object (e.g., product, process, system), the following research string has been used in Google Scholar (for publications in English, and up to 2021): {life cycle assessment OR life cycle analysis OR LCA OR environmental footprint OR life cycle cost OR LCC} AND {circular economy OR circularity} AND {indicators OR metrics OR indexes OR measurement}. In all, ten peer-reviewed studies experimenting with both life cycle–based indicators and circularity indicators have been found and selected for in-depth analysis and comparison.

Life Cycle Assessment Indicators

Life cycle assessment (LCA) is an internationally standardized methodology (ISO 14040-14044, 2006) used for the quantitative environmental impact assessment of products, processes, services, and systems, throughout their life cycles, i.e., from materials acquisition to processing, transportation, usage, and end-of-life phases [11, 12]. LCA enables the systematic analysis of material and energy flows associated with products, processes, industrial sectors, and economies. LCA is at the foundation of industrial ecology [13], which seeks to design and manage products and services that meet human needs in a sustainable manner [14]. LCA can be particularly useful in comparing alternate strategies, understanding the trade-offs between benefits and impacts of different systems, and thereby, making informed decisions [15–17]. According to ISO standards 14,040 (2006) [11] and 14,044 (2006) [12], the purpose of the life cycle impact assessment (LCIA) phase is to establish a linkage between the inventory of elementary flows in the system under study and their potential environmental impacts related to the induced ecological mechanisms. In particular, environmental impact indicators measure the damage caused by human-made actions and products on ecological categories. For instance, the ReCiPe LCIA methodology is a robust impact calculation method that provides characterization factors and normalization methods for calculating impact [18]. Note that other LCIA methodologies are available to perform an LCA, including complementary or supplementary indicators such as IMPACT 2002+ or CML-IA, as listed in the International Life Cycle Data System (ILCD) Handbook [19].

The state-of-the-art ReCiPe 2016 Midpoint (H) indicators are the ones used in the current project (see Part II). The ReCiPe Midpoint indicators notably quantify the environmental damage in 18 categories, including, for example, global warming potential (kg CO_2 eq.), stratospheric ozone depletion (kg CFC11 eq.), terrestrial acidification (kg SO_2 eq.), freshwater ecotoxicity (kg 1,4-DCB), and human carcinogenic toxicity (kg 1,4-DCB). A detailed description of the ReCiPe LCIA methodology can be found in Huijbregts et al. (2017) [18]. The 1.10 version of OpenLCA (open access LCA software) [20] was used to model the three product alternatives and to conduct the comparative

LCA. Within OpenLCA, the ecoinvent database 3.2 [21, 22] and the LCIA ReCiPe 2016 Midpoint (H) have been used to perform the environmental evaluation.

Meanwhile, note that while conducting an LCA is a sound and relevant approach for the quantitative environmental impact assessment of products, it has been stated that its actual applicability in the context of the *ex-ante* evaluation of CE strategies and support for early decision-making is often limited [23]. Further roadblocks of the use of LCA in the industry have been highlighted in the literature [24, 25]: (i) performing an LCA is often a complex and expert-level task, and communicating the results also requires a certain level of expertise, or the support from environmental experts; (ii) collecting and compiling data (life cycle inventory) can be time-consuming and costly; and (iii) LCA does not allow to identify hotspots or improvement scenarios quickly and to decide between environmental trade-offs in a straightforward manner, as it is further illustrated and discussed through the experimentations made in Part II of this study. Indeed, one of the aims of this project is to get feedback from future engineers on the applicability and practicability of LCA in comparison with circularity and leading sustainability indicator-based approaches to assess and develop more circular and sustainable products. While LCA-based indicators can be relevant in evaluating the CE performance of products, it appears that several indicators have recently evolved from material flow and life cycle perspective [26, 27], including novel leading sustainability indicators and potentially more appropriate circularity indicators, as further detailed in the following sub-sections.

Leading Sustainability Indicators

Sustainability indicators have been comprehensively reviewed by scholars. Their classification is widely acknowledged and often associated with the TBL dimensions, namely economic, environmental, and social indicators [28, 29]. Kravchenko et al. (2020) built an Excel-based repository of over 290 leading sustainability-related performance indicators that are organized under key CE strategies and business processes [30]. The CE strategies included are the following: upgrade, repair, and maintenance, reuse, refurbish, remanufacture, repurpose, recycle/cascade, recover, reduce, restore, avoid impacts in raw material sourcing, manufacturing, and product use phase, reinvent the paradigm, and rethink value generation. This database is linked to a decision-making tool for selecting a relevant set of performance indicators to inform and support decisions, aiming at the sustainability screening of alternative circular solutions in terms of environmental, social, and business potential. In the present project, this Excel-based tool [30] has been used by the engineering students to identify and select the leading sustainability indicators relevant to compare the three product alternatives (see Part II).

Importantly, leading environmental performance indicators have the ability to produce simpler measures of environmental aspects that can inspire effective actions for improving the environmental performance of products [23]. Leading s-indicators appear thus as an ad hoc and commendable solution to assess the sustainability performance of CE initiatives: "For a meaningful ex-ante sustainability assessment, leading indicators are preferred over lagging, as they can be used to plan and monitor the effectiveness of proposed actions by focusing on critical areas or resolving any uncertainty early in the planning and development process" [23]. In fact, leading indicators influence future performance and give future prediction and changes in the future economic cycle. They are considered simple "input/output" indicators, and thus offer better measurability and control over impact. Examples of leading s-indicators include the following: (i) on the economic side, the total material costs, processing cost per unit, cost

of user education, or maintainable period after sales; (ii) on the environmental side, the fraction of renewable raw materials, the fraction of reused components, or energy consumption for disassembly; and (iii) on the social side, the mist/dust level at working stations, or exposure to corrosive/toxic chemicals. On the other hand, lagging indicators analyze past performance, give past data, and delayed reaction to the economic cycle. They are considered "outcome/impact" indicators (e.g., global warming potential, ozone depletion, customer retention, gross margin) and offer a higher certainty of data (e.g., LCIA results).

Circularity Indicators

In parallel, the number of circularity indicators has considerably increased in the past few years, leading to both utility and fuzziness regarding their purpose and application. C-indicators can be defined as measuring instruments aiming to quantify the performance and progress of systems from a CE perspective [31]. Here, to evaluate, compare, and augment the circularity of the three product alternatives used for this project, the focus is put on product circularity indicators [32], i.e., at the micro-scale of CE implementation [33–36]. More details on the classification of CE indicators can be found in the taxonomy of the 55 sets of c-indicators proposed by Saidani et al. (2019) [37] and in the multiple correspondence analysis of 63 CE metrics made by Parchomenko et al. (2019) [32]. More recently, based on an up-to-date and systematic literature review, Ross Lindgreen et al. (2020) performed a critical analysis on 74 approaches, methods, and tools to assess CE at the micro-level [35]. On this basis, they advocated for a closer collaboration between researchers and practitioners to consider end-user needs in the design of CE assessment approaches.

Additionally, through a previous workshop experimenting with four c-indicators on an industrial product [31], empirical pieces of evidence have been brought on how product c-indicators can be suitable to help design more circular products. The material circularity indicator (MCI), circular economy indicator prototype (CEIP), circularity potential indicator (CPI), and circular economy toolkit (CET) have been positioned among the pool of eco-design tools and along the design and development process of products. It has been shown that they can quickly guide practitioners towards areas of improvement and promising CE strategies. In the present study, nine product c-indicators are tested by two consecutive classes (in 2020 and 2021) of engineering master students, namely (i) the MCI, (ii) CEIP, (iii) CPI, (iv) CET, (v) circularity calculator (CC), (vi) circular economy index (CEI), (vii) circularity (CIRC), and longevity (LONG) indicators. More information for each of these c-indicators can be found in the database linked to the taxonomy of CE indicators [37], now available online (http://circulareconomyindicators.com/). The latest c-indicator that has been experimented, during the second session (class of 2021), is the concept circularity evaluation tool (CCET) [38]. The Excel-based CCET has been developed for the evaluation of alternative product concepts in terms of their circularity potential in the early stages of product design and development.

Results

Trade-offs Between the Circularity and Sustainability Performance of Products

Nikolaou et al. (2021) examined the existing CE and sustainability literature on a triple-level analysis (at a micro-, meso-, and macro-level) within the engineering and management fields [39]. They noted that although some scholars support the positive effects of CE

practices on the production stages, others emphasize its adverse effects on the environment and natural resources. As such, they concluded that the eco-efficiency of resources and the positive impacts of CE on sustainability are a crucial academic area that should be further examined by researchers [39]. Bocken et al. (2021) provided an up-to-date landscape and classification over time of circular and sustainable business model experimentations [40], including a mapping by (i) types of experiments (business experiment case, experimentation as research method, review/conceptual work), (ii) research domains (transitions, business, engineering, design), and (iii) tools and approaches (lean startup, effectuation, business model canvas, innovation funnel). Similar to the experimentation of circular and sustainable business models, the application of circularity indicators and their positioning among other tools such as LCA to design more circular and sustainable systems is still emerging [40].

According to Geissdoerfer et al. (2017), the TBL is the system prioritized for sustainability, while the economic system is prioritized in a CE with the goal of eliminating all resource inputs into and leakages out of the system [41]. Three main relationship types between the CE and sustainability have been conceptualized and formalized [41]: (i) conditional relation (i.e., CE is one of the conditions for a sustainable system, could be necessary but not sufficient); (ii) beneficial relation (i.e., more circularity induces more sustainability); and (iii) trade-off relation (e.g., a CE strategy having costs and benefits in regard to sustainability). In this line, Schroeder et al. (2019) positioned the contribution of CE practices to the SDGs [42]. CE practices can have a strong link and direct contribution to several SDGs, such as the SDG 12 "Responsible consumption and production," and an indirect contribution to complementary SDGs, such as the SDG 11 "Sustainable cities and communities." In parallel, achieving key targets related to other SDGs, such as the SDG 9 "Industry, innovation and infrastructure" or SDG 13 "Climate action," could contribute towards augmented CE practices.

Nevertheless, the aggregation of sustainability-related indicators is still a debated challenge for sound decision-making and well-justified interpretations [43]. In practice, decision-making for product circularity and sustainability could be a challenging task, where complex trade-offs might occur, such as a design decision between the minimization of energy use or the reduction of waste generation. More sustainability-related trade-off types, situations, and occurrences are described in Kravchenko et al. (2020) [30]. These trade-offs between sustainability and circularity aspects, when not considered or misinterpreted, may lead to uninformed decision-making and undesired outcomes. On this basis, Kravchenko et al. (2020) came up with four critical criteria to integrate when developing decision support tools to deal with sustainability-related trade-off situations [30]: (i) it is fundamental "to enable elicitation of sustainability objectives and use relevant tools to reveal trade-offs"; (ii) it is important "to provide several prioritization principles in conjunction to assist trade-offs understanding and management"; (iii) it is key "to enable the evaluation of trade-off acceptability"; and (iv) it is essential "to develop tools and procedures that are relatively easy to be implemented by industrial practitioners" [30].

Additionally, life cycle thinking and CE can "interact and feed off each other" [6]. On the one hand, c-indicators can be deployed during the eco-design process [30]. On the other hand, LCA can be used to evaluate CE projects. Still, in this case, it is not free from methodological challenges such as the impact allocation of CE loops, e.g., between different stakeholders or for multiple life products and components, although, in some cases, CE and LCA can have opposing views. In fact, product circularity, material efficiency, and environmental performance do not necessarily correlate [44]. For instance, the pure application of CE principles would basically encourage recycling, while energy recovery could

sometimes be more beneficial [6], according to an LCA. Also, from a life cycle perspective, systematically seeking to close-the-loop using recycled materials (e.g., recycled plastics) is not always the most sustainable solution in comparison to the use of new plastics, e.g., leading to weight reduction in transportation systems and thus decreasing the fuel consumption and related emissions over their lifetime [45, 46]. More recently, Niero et al. (2021) investigated if "life cycle assessment enough to address unintended side effects from circular economy initiatives?" [47]. They argued that the ability of LCA to address rebound effects from CE initiatives is limited because "LCA can model how different product systems interact with each other, but does not attend to the socio-technical dynamics taking place within and across different life cycle phases" [47].

Connection Between LCA-Based and Circularity Indicators

In what follows, we review, analyze, and discuss the extant connection (i.e., the possible synergies, complementarities, or conflicts) between the outputs of LCA-, c-indicator-, and s-indicator-based approaches published in the literature, according to the three main relationship types between the CE and sustainability aforementioned, namely (i) conditional, (ii) beneficial, and (iii) trade-off relations. To ensure the scientific soundness (i.e., the rigor, reliability, and validity) of the case studies scrutinized here, only examples from international peer-reviewed journals are considered. In all, ten independent studies experimenting and comparing LCA and C-indicators concurrently on the same application cases have been found, as described hereafter and synthesized in Table 1. Note that while several recent studies are covering both sustainability and circular economy concurrently [3, 5], this study only focuses on quantitative studies applying LCA- and circularity-based indicators on the same case studies, for comparison purposes and analysis of trade-offs.

Walker et al. (2018) used an LCA-based approach to calculate the potential environmental impact of five CE scenarios in terms of carbon footprint [48]. In their case study on tidal turbine parts, they included the recovery and reuse of materials from the supply chain and at end-of-life. The results were compared to three material circularity indicators, namely the MCI, CET, and CEIP. The two takeaways of their study were the following: (i) "LCA methodologies based around end-of-life approaches are well placed for quantifying the environmental benefits of material efficiency and CE strategies; and (ii) when applying indicators relating to the circularity of materials, these should also be supported by LCA-based studies" [48]. Overall, in their case study, an increase in the c-indicators score leads to a reduction of the carbon footprint.

Other researchers started to investigate (i) whether c-indicators and LCA provide the same results in the assessment of circular strategies and (ii) what are the challenges of applying LCA to a circular system. Interestingly, two case studies were carried out by scientific from the International Reference Center for Life Cycle of Products, Services and Systems (CIRAIG) to bring new elements on this topical issue: (i) one on the end-of-life management of tires [49] and (ii) one on a closed-loop system for plastic bottle [44]. According to Lonca et al. (2020), there are two implicit assumptions behind the construction of c-indicators that need to be checked [44]: (i) closing material loops at a product level leads to improvements in material efficiency for the economy as a whole, and (ii) maximizing material circularity contributes to mitigating environmental impacts (i.e., increasing the recirculation of materials instead of using virgin material supply should translate into broader environmental benefits). The authors tested these two statements at different scales through a case study on the circularity plastic bottles made of PET in the

Table 1 Connection between LCA, sustainability, and circularity indicators in the literature

Authors	Sustainability/LCA indicators	Circularity indicators	Types of relations	Products/sectors	CE scenarios
Walker et al. (2018) [48]	Global warming potential	MCI; CET; CEIP	Beneficial	Tidal turbine	Reuse; recovery
Lonca et al. (2018) [49]	Human health; ecosystem quality	MCI	Trade-offs (scenario-dependent)	Tires	Regrooving; retreading
Niero and Kalmar (2019) [26]	Global warming potential; abiotic resource depletion; acidification; particulate matter; water consumption	MCI; MRS	Trade-offs (scenario-dependent)	Packaging	Recycling; reuse
Lonca et al. (2020) [44]	Global warming potential	MCI	Trade-offs (scenario-dependent)	Plastic bottles	Recycling; closed-loop; bio-based
Linder et al. (2020) [7]	Global warming potential; abiotic resource depletion; environmental priority strategies	PCM	Beneficial/conditional	Set of 18 products (arm-chair, elevator, laptop, etc.)	Maintenance; reuse; recycling; renewable; refurbishing; remanufacturing
Bracquené et al. (2020) [50]	ReCiPe (H) Endpoint	PCI, a derivate of the MCI	Beneficial (under certain conditions)	Washing machines	Circular material sourcing; recycling; PSS
Braakman et al. (2021) [51]	Life cycle costs	BCI, a derivate of the MCI	Beneficial (up to a certain limit)	Building	Recycling; bio-based
Schulte et al. (2021) [52]	Global warming potential	CIRC	Beneficial/conditional	Catheter	Remanufacturing
Rufí-Salís et al. (2021) [54]	Global warming potential; freshwater eutrophication; marine eutrophication; ecotoxicity; cumulative energy	MCI	Trade-offs	Urban agriculture	Bio-based; recycling; compost
Glogic et al. (2021) [55]	Human health; ecosystem quality; resource depletion	MCI	Beneficial	Alkaline batteries	Recycling

US market. To do so, they combined the MCI and LCA to both assess the material efficiency and environmental performance [44]. On one side, the MCI showed that closing the material loops at the product level increases material circularity for specific plastic bottle brands but not in the PET market as a whole. On the other side, LCA indicators revealed that increasing the closed-loop recycling of PET bottles is environmentally beneficial at a product level.

Such trade-offs can be mapped in a two-dimensional chart (e.g., with the x-axis representing the circularity performance, and the y-axis the reduction of environmental impacts, where quadrants I (upper left corner) and III (lower right corner), being the ones with trade-offs on circularity and environmental impacts, quadrant II (upper right corner) delimitating a win-win situation, and quadrant IV (lower left corner) a lose-lose situation). On this basis, Lonca et al. (2018) compared two circularity strategies (regrooving and retreading) to recover end-of-life tires from heavy-duty vehicles in Brazil [49]: (i) regrooving allowed an increase of the lifetime by 30.5% and a decrease of fuel consumption by 5.4%, while (ii) retreading increased the lifetime by 50% but augmented the consumption of duel by 6.8%. Considering both the MCI (for circularity) and ReCiPe Endpoints indicators (human health and ecosystem quality), the regrooving option was situated in quadrant II (beneficial, win-win situation) while the retreading option was in between quadrants I and IV (showing critical trade-offs).

Niero and Kalbar (2019) coupled five LCA-based indicators with two material circularity-based indicators via multicriteria decision analysis (MCDA) to deal with conflicting situations where the selection of the best product alternative or strategy can be influenced and biased by the choice of a specific indicator [26]. The two material c-indicators considered were (i) the MCI and (ii) the material reutilization score (MRS). The five environmental impact indicators were (i) climate change, (ii) abiotic resource depletion, (iii) acidification, (iv) particulate matter, and (v) water consumption. Applied to different packaging alternatives, the separate use of c-indicators and LCA-based indicators resulted in trade-offs, and no alternative could have been thus easily selected. To resolve these trade-offs or conflicts, they applied the MCDA method TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to rank the alternatives and identify the best one. Yet, using a similar approach to other cases or with other indicators, it is not guaranteed that different weighting configurations would not lead to different results.

Linder et al. (2020) also noticed that there are few published empirical tests of c-indicators, notably on the same test across more than one product or several variations of a similar product [7]. To bridge part of this gap, they applied their product-level circularity metric (PCM) to a set of 18 products and compared the PCM scores to three environmental impact indicators calculated through LCA, namely (i) global warming potential, (ii) abiotic depletion potential, and (iii) environmental priority strategies. For each of these LCA-based indicators, the authors found an inverse relationship between a product's PCM score and the LCA score, meaning that a higher circularity performance leads to a diminution of environmental impacts for their experimental sample of 18 products. While Linder and his colleagues (2020) acknowledged that their results could not be generalized to all products in all places [7], they gave a relevant contribution in understanding the general relationship between product-level circularity and environmental impact. If similar results and correspondence could be achieved for a wider pool of products and c-indicators, the use of these c-indicators would offer industrialists an alternative to conducting lengthy and labor-intensive LCA. Indeed, while the authors demonstrated that the PCM is relatively inexpensive to estimate and easy to interpret for simple manufactured products, they mentioned it is not optimal to deal with more complex products that have many different cycles

and sub-assemblies [7]. As such, they encourage future research work to conduct similar tests to a larger variety of products and c-indicators.

Bracquené et al. (2020) applied the product circularity indicator (PCI) to a case study for circular washing machines [50]. The potential trade-off between increasing circularity and minimizing the environmental burden of the washing machines has been investigated using attributional LCA to quantify the potential environmental impact of the product system. For the LCA part, the ecoinvent database 3.3 and the ReCiPe (H) Endpoint method with the European dataset have been deployed. The authors compared the PCI (score between 0 and 1, which measures the circularity of flows) and LCA results (environmental burden in eco-Pts) for the baseline with five improvement strategies based on CE thinking: material selection, collection rate, material recycling, enhanced recycling, and product-service system (PSS). Due to the high energy consumption during each wash cycle, the use phase was identified as the life stage with the highest environmental burden. This highlighted the first potential trade-off when dealing with energy-using products because the circularity measure does not take into account the burden of energy requirement during the use phase. Though, in total, the LCA results confirmed that the PSS strategy could both increase the circularity and decrease the environmental burden of the product system, under the following condition: the washing machines can be successfully refurbished every six years, and the majority of the components can be reused three times.

Braakman et al. (2021) investigated the influence of building design on life cycle costs (LCC) and level of circularity (LoC) [51]. The relationship between the LCC and the LoC was quantified using the building circularity indicators (BCI), which is a derivative of the MCI customed for the construction and building industry. When replacing virgin materials with recycled or biological materials and using building products that can be disassembled relatively easily, the results showed that it is possible to double the LoC to 0.41 compared to the initial design having an LoC of 0.20 [51]. The results also revealed that increasing the circularity level would result in a considerable increase in the product costs. Schulte et al. (2021) deployed both LCA and a circularity indicator measuring multiple life cycles to compare the environmental and systemic differences between a newly manufactured catheter and a remanufacturing one [52]. From the LCA standpoint, the results revealed that using the remanufactured catheter reduces the global warming impact by 50.4% and the abiotic resource use by 28.8%. They notably used an ad hoc version of the CIRC indicator developed by Figge et al. (2018) [53], which quantifies the number of times a resource passes a product system through different product cycles in the value chain [52]. Overall, the circular product system showed a decrease in the environmental impact mainly due to the mitigation of primary plastic production and processing, though the circular product system requires more electricity, as well as detergents disinfectants to close the loop. From the system perspective, the findings suggested that the environmental savings increase with increasing collection rates of catheters.

Rufí-Salís et al. (2021) examined the environmental and circularity performance of different CE strategies in urban agriculture systems [54]. They combined LCA and the MCI to compare "the baseline scenario of a Mediterranean rooftop greenhouse with 13 CE strategies" [54]. The results show that "the MCI score for all strategies was biased by overweighting of the water subsystem in the mass balance" [54]. To address this issue, they came up with a series of modifications to the circularity assessment, calculating specific MCI scores for every subsystem before coupling them with LCA indicators. Glogic et al. (2021) also combined MCI and LCA scores to several scenarios for the circularity improvement of alkaline batteries while considering their potential impacts on the environment concurrently [55]. Their results showed that improving circularity generally

contributes to a mitigation of the environmental impacts, but with a specific variability depending on the circular scenarios. For instance, an increase of MCI score by 14% for two recycling scenarios could translate to a slight reduction of impacts in one case (from 0.06 to 1.6%) and a large reduction in another (from 9.8 to 56.2%). Note that other recent studies have quantified different circular and end-of-life scenarios using LCA (e.g., Levänen et al., 2021), showing trade-offs as well between circularity and environmental sustainability, but these are out of the scope of the present study as they are not directly or purposefully comparing the LCA results with any specific and quantitative circularity indicators [56].

Discussion and Perspectives

The connection between circularity scores and environmental performance quantified through LCA has recently been investigated by numerous authors. While they are demonstrating different types of relationships, as summarized in Table 1, the current and available studies present several shortcomings, including (i) a lack of diversity in the product-level c-indicators tested (most intrinsic c-indicators measuring the circularity of material flows such as the MCI), (ii) a lack of comparison between the different c-indicators deployed within the same study, (iii) a lack of discussion on potential environmental impact trade-offs between different LCA indicators when comparing multiple CE strategies, and (iv) a lack of critical analysis and feedback on the complementary between LCA and circularity indicator-based tools. In fact, these existing studies mainly focused on the quantitative intrinsic results of LCA-based and circularity-based indicators, without discussing, e.g., their usability, ease of implementation, or robustness to actually being deployed practically and in a sound manner during the design and development process. In addition, as the TBL approach to sustainability measurement includes environmental, economic, and social indicators, Boyer et al. (2021) recently argued that the assessment of the circularity performance should consider three dimensions [57]: "(i) high material recirculation, (ii) high utilization, and (iii) high endurance in products and service offerings" [57].

As Mannan and Al-Ghamdi recall (2022), "the combination of LCA and CE can result in more in-depth analysis and a better understanding of economic, social, and environmental sustainability" [58]. In this line, further studies need to be conducted to systematically validate the underlying assumption that going towards more circularity would bring more sustainable benefits to take advantage of the cheaper and more accessible approach that c-indicators could bring in various industrial and business practices [7]. Ideally, providing the tool, framework, or platform, enabling the automatic evaluation of whether an enhancement of the circularity performance leads to sustainable benefits would be great and timely progress in this field. Also, while the scope of this project is focusing on products, it would be interesting to gain additional insights on the use of life cycle- and circularity-based approaches to assess, monitor, and improve the sustainability and circularity performance at different levels of the CE implementation, such as the company level [59]. Thus, additional case studies are still needed to draw more robust and solid conclusions, as well as to further experiment how different practitioners (e.g., novices, students, LCA experts, seniors in the industry) handle these different indicator-based approaches for more circularity and sustainability. Importantly, as the ISO standard for measuring and assessing circularity is still under development (see the ISO Technical Committee ISO/TC 323), such complementary studies would be of utmost importance.

With this background, Part II of this study expands on previous studies attempting to link quantitatively the circularity scores and the environmental performance. Concretely, to fill the gaps of existing studies, 18 life cycle assessment midpoint indicators, nine product circularity indicators, and 50+ sustainability indicators are computed and compared, in all, by 38 groups of four to five engineering students over two consecutive classes. To compare the outputs generated by these indicators, the engineering students had the same dataset to quantify the performance of three different products of the same product family: a conventional gasoline walk-behind lawn mower, an electric walk-behind lawn mower, and an electric autonomous lawn mower. Last but not least, practical recommendations and guidance on how to combine existing approaches are given and justified thanks to the new insights generated by this project, including comparative quantitative results combined with qualitative feedback and critical analysis from engineering students.

Author Contribution Michael Saidani: Conceptualization; data curation; formal analysis; investigation; methodology; writing (original draft); writing (review and editing). Harrison Kim: supervision; validation; writing (review and editing).

Data Availability Available on demand.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

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