Benchmark of Circularity Indicators and Links with Life Cycle Assessment

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Abstract. Deploying the right circularity indicators (c-indicators) is key to assessing and improving the performance of products, companies, and regions from a circular economy (CE) perspective. Building on the initial taxonomy of c-indicators, this project extends the identification of sets of c-indicators to more than 100. Working with a think tank of CE experts from major French industrial companies, five new features have been added to better characterize a set of c-indicators to its practical use in an industrial context. These new features are: (i) CE spheres considered, (ii) life cycle stages covered, (iii) the availability of use cases, (iv) the popularity, and (v) transparency. Statistical trends and critical analysis on these c-indicators are then given. On this basis, a set of ten complementary c-indicators is particularly proposed, covering a wider spectrum of the CE paradigm, including, e.g., material flow, energy flow, impact, design, and corporate-based indicators. In practice, to support decision-makers in the industry (e.g., managers, engineers, product leaders, designers) compute and deploy appropriately these c-indicators, a new and highly visual factsheet for c-indicators is developed. Last but not least, discussion on the articulation, positioning, and potential trade-offs between c-indicators and LCA-based indicators are made through different scenarios and illustrative examples.

1 Introduction: context and objectives

A common vision – shared by academics, industry, and governmental agencies – has emerged on the need to measure the progress and impacts of the transition towards a circular economy (CE) [1-3]. Thus, many circularity indicators (c-indicators) have been developed in recent years as tools and catalysts towards more circular practices, under the *sine qua non* condition that the actors involved in this transition can have access to and properly employ the indicators that are most appropriate for them. However, the progressive development, outside of any normative context, of these indicators has led to the heterogeneity of approaches to measure circularity [3]. The aim of this project was thus to provide clarity on this multitude of available indicators, as well as to help select a set of c-indicators that are the most relevant,

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specific, and operational for an organization. The main objective of this study was to provide industrial practitioners with operational, complete, and harmonized indicators to measure the circularity of their activities. The secondary objective of this study was to make the link with other methods, in particular life cycle assessment (LCA), to integrate these indicators into existing environmental assessment tools, when relevant. In this line, this piece of research complements recent works, investigating the topics of CE and LCA, by combining the analysis of c-indicators [4, 5] and their connections with life cycle impact assessment [6-8]. The present study is structured into three parts: state of the art, detailed analysis, and recommendations (see Fig. 1).

Fig. 1. Research synopsis

2 Literature review

2.1 Inventory and classification of circularity indicators

The present literature survey consisted of updating the initial taxonomy of c-indicators [4] with the c-indicators released in the 2019–2020 period. This work led to the creation of an online tool, the Circularity Indicators Advisor (http://circulareconomyindicators.com/). The new bibliographical search, which was completed at the end of 2020, led to the identification of a total of 105 references corresponding to as many sets of c-indicators. All these c-indicators are listed and referenced in an Excel spreadsheet, as one of the main deliverables of this study and available on-demand. Fig. 2 shows the set of classification criteria used. In comparison with the initial taxonomy of c-indicators [4]. this figure shows an increase in the number of suitable categories to classify, differentiate and select appropriate c-indicators, based on a review of existing literature and feedback from industrial participants.

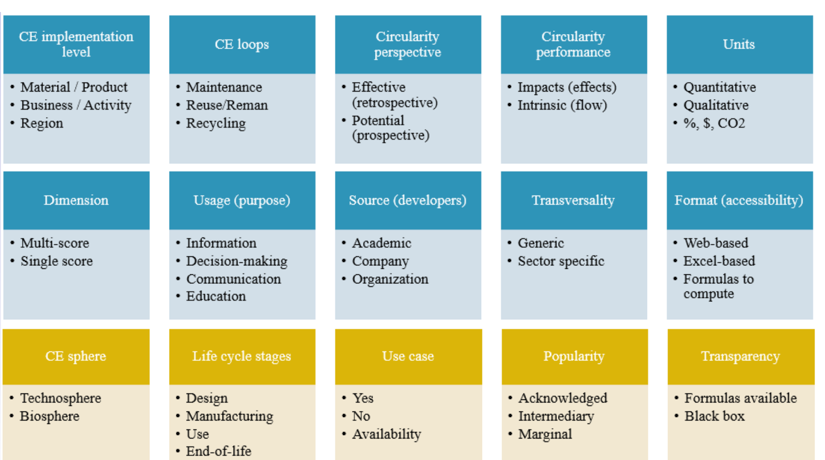

Fig. 2. Set of classification criteria used for the analysis and selection of circularity indicators (the ten initial criteria in blue [3], the five new criteria in gold)

2.2 Structured description of the state of c-indicators

Based on the aforementioned criteria (see Fig. 2) to classify these 105 sets of c-indicators, some interesting trends emerged regarding their distribution among key categories. First, the majority of these newly developed c-indicators have been created in an academic context (71 c-indicators), compared to the ones established by industry or consulting agencies (16 c-indicators), or by organizations (18 c-indicators). Second, regarding their application, only 20 sets of c-indicators are sector-specific indicators, while the remaining 85 c-indicators can be applied cross-sector. Among the 20 sets of industry-specific c-indicators, the building and construction (including deconstruction) sector is the most advanced in terms of sector-specific indicators. Third, less than one-third of c-indicators (29 c-indicators) is designed to assess a circularity potential. Complementary to effective c-indicators, a circularity potential indicates how circular-ready a product, process, or system is before reaching its end-of-life and/or CE loop(s). Potential c-indicators are particularly useful and developed at a micro-level of the CE [5], e.g., to be deployed when designing new products to assess their circularity potential. Last but not least, less than half of the sets of c-indicators (48 c-indicators) take into account more than two CE loops (e.g., recycling, reuse, remanufacturing and/or maintenance) concurrently.

3 In-depth analysis of 10 sets of c-indicators

3.1 Selection process of c-indicators

Different criteria were used to filter out and select an ad hoc set of ten c-indicators for the industrial companies involved in this project. First, the emphasis was on selecting a set of complementary indicators covering a complete spectrum of the CE paradigm, including, e.g., material flow, energy flow, impact, design, and corporate-based indicators. Particularly, requirements from the industrial members supporting this project included the need for: sectoral indicators (specific to the industrial sector); micro-level indicators (at the product or project level); and meso indicators (for reporting and steering at the company level). Then, additional critical criteria for selecting *ad hoc* c-indicators were their transparency and operationality (i.e., availability of the method and/or formula for calculating the c-indicator). The final selection of a specific c-indicator from a particular category judged to be the most appropriate indicator (e.g., which recycling indicator to choose from among all the recycling indicators), was ultimately based on the authors' expertise and confronted with a discussion and validation with the industrial partners. Note that when more than one c-indicator is recommended by category (e.g., three material flow analysis-related c-indicators for the factsheet 6 in Table 1), it means that the c-indicators are complementary to ensure a higher level of completeness to assess circularity within this specific category.

3.2 Detail of the c-indicators selected and associated factsheets

Following the process described in the previous sub-section, a shortlist of *ad hoc* c-indicators is provided in Table 1. The detailed description of these c-indicators, according to the 15 characterization criteria depicted in sub-section 2.1, is available on the Excel spreadsheet updated during this project and available on-demand (michael.saidani@centralesupelec.fr). In practice, to support decision-makers in the industry (e.g., managers, engineers, product leaders, designers) compute and appropriately deploy these c-indicators, a new and highly visual factsheet for c-indicators has been designed for each of the c-indicators listed in Table 1. Due to space limitations, the reader is invited to contact the authors to have access to these factsheets. One can also access the taxonomy of c-indicators [4] and its online tool (http://circulareconomyindicators.com/) – freely accessible – to get further details and apply these c-indicators.

Table 1. 10 factsheets associated with the selected circularity indicators

Categories	Indicators	Acronyms	Tools
Factsheet 1: Circularity performance at the company level	Circulytics	Circulytics	Web-based
	Circular Transition Indicators	CTI	Web-based
Factsheet 2: Circularity at the material level	Material Circularity Indicator	MCI	Excel
Factsheet 3: Circularity at the product level	Product Circularity Indicator	PCI	Excel
Factsheet 4: Circularity of design alternatives	Concept Circularity Evaluation Tool	CCET	Excel
Factsheet 5: Reuse and life extension	Reuse Potential Indicator Circularity and Longevity Indicators	RPI CLI	Formulas
Factsheet 6: Material flow (MFA-like)	End-of-Life Recycling Rate Recycled Content Old Scrap Ratio	EoL-RR RC OSR	Formulas
Factsheet 7: Energy flow	Circularity Index	CI	Formulas
	Circularity of Material Quality	Qc	Formulas
Factsheet 8: Circularity at a territorial level	Regional Material Flow tools for the Circular Economy	RMFCE	Formulas Excel
Factsheet 9: Environmental impact of circularity	Recycle Benefit Rate Recycled Content Benefit Rate	RBR RCBR	Formulas
Factsheet 10: Socio-economic impact	Socio-economic Indicator for EoL Strategies for Bio-based Products Total Circular Revenue Total Cost of Ownership	SEI-EoL TCR TCO	Formulas

4 Links with life cycle assessment

In this section, we discuss and illustrate possible synergies and/or conflicts (trade-offs) between LCA and c-indicators. While we adopt the standpoint that the CE remains (or should remain) a means to achieve the environmental, societal, and economic objectives of sustainable development, it becomes of particular interest to understand when circularity does (and does not) work towards sustainable development, and which parameters in the CE loops are critical. We can imagine three possible avenues to explore the links between LCA and c-indicators: (i) LCA output data (e.g., flows/midpoints/endpoints) are used as input data for the calculation of c-indicators; (ii) c-indicators are integrated into the LCA output as a flow/midpoint/endpoint indicator [6]; and, (iii) LCA is used to verify the soundness of a set of c-indicators (e.g., to be validated on sets of products, to save time compared to performing an LCA). On the one hand, CE focuses on maintaining (preserving and increasing) resource values in the economy. As such, CE considers different levels of application: at the macro level, it focuses on material exchanges between the economy and the environment; at the structural or meso level, the emphasis is on material flows in industrial systems, distinguishing not only categories of materials but also sectors and industrial branches; at the micro or business level, it focuses on firms and their products. CE strategies often assume that it is always good to keep individual resources within the economy, either in use for as long as possible or through cycling loops in technical or biological cycles. On the other hand, LCA focuses mainly on the product level and on all the impacts associated with the product life cycle. LCA does not advocate for any specific (e.g., linear or circular) strategy but also provides an assessment framework to understand the environmental implications of different options associated to a product and/or service. In this way, LCA can serve as the science-based methodology to assess the benefits or otherwise of specific CE strategies, as well as to understand the conditions where keeping the resources within the economy for longer may actually be counter-productive (e.g., due to the costs of removing toxic substances contaminating such resources) [7, 8].

In all, combining c-indicators with LCA allows for identifying environmental trade-offs of circularity choices [9-12]. However, in some cases, the application of CE strategies and LCA can have opposing views. CE principles would encourage recycling (no questions asked), while according to LCA, energy recovery is sometimes more beneficial [8]. Additionally, LCA does not yet have all the answers when dealing with CE projects. For example, addressing the dissipative losses of raw materials is hardly taken into account by standard resource depletion indicators. Also, downcycling and upcycling are not straightforward to evaluate [8]. Interestingly, to bring new insights into the question "Do c-indicators and LCA provide the same results in the assessment of circular strategies?", the researchers from the International Reference Center for Life Cycle of Products, Processes and Services (CIRAIG) [10, 11] compared circularity and LCA indicators for CE strategies on two industrial case studies: (i) increasing circularity for a plastic product company; (ii) end-of-life strategies for used tires. Importantly, current research gaps on circularity and LCA include: to better understand how results are affected by methodological differences and limitations, e.g., the end-of-life allocation approaches (cut-off, system expansion, hybrid approach), the difference between consequential versus attributional approach (i.e., considering rebound effects on other actors and parts of the system), and the evaluation of secondary material quality loss. Last but not least, it is important to recall here that seeking to maximize the circularity performance or score is not always the best option in terms of the costs and energy to be deployed (e.g., related to reverse logistics to collect all products, processing of certain materials). Indeed, achieving 100% circularity is often incompatible with the current industrial economic reality, end-of-life channels, and available technologies. In this sense, circularity performance should be used and optimized as a lever (i.e., as a cursor to be adjusted) to guarantee economic and environmental benefits. In practice, the trade-offs between economic, ecological, and circularity performance should be considered and optimized simultaneously. In this line, a mathematical optimization model has been developed to find the circularity performance(s), maximizing the profile and minimizing the carbon footprint [9].

5 Conclusion and perspectives

Deploying the most appropriate c-indicators is essential to both assess and improve the performance of products, companies, and regions in a circular and sustainable economy perspective. In practice, although a wide variety of indicators have been developed in recent years, it remains to be seen how widely they have been adopted and how mature they are in their adoption by industrial players, particularly in an integrated way during the design and development process. On the one hand, it seems that these c-indicators – which can be considered as high-level heuristics or time-efficient key performance indicators – and their associated tools are more rapidly deployable and easier to understand than certain environmental assessment methods and indicators such as LCA. On the other hand, to support sustainable decision-making, it remains essential to provide tangible proof that these indicators are correlated with an economic, environmental and/or societal improvement. The present contributions – e.g., the database of more than a hundred c-indicators – can serve as a solid basis for recombining indicators based on their complementarity, as well as for enriching them with their respective specificities to build new indicators that respond better to the specific contexts and needs of industrialists. The results of this project can also be used as inputs for the upcoming standard on CE measurement (see ISO/TC 323 [13]).

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