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Comparative analysis of micro level indicators for evaluating the progress towards a circular economy

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A R T I C L E I N F O

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A B S T R A C T

With the transition from a linear to a more circular economic model, tools are required to monitor the effect of adopted changes, and to assist in further decision-making along time. Within this context, circularity micro-indicators have been proposed by many authors as a fairly simple tool to measure progress towards a more circular economy, at the product or company level. However, these circularity micro-indicators do not follow a standard, vary widely in complexity and approach, and some of them are extremely narrow focused on only a few aspects of the entire product life cycle, hampering their practical adoption by companies. Based on existing literature on categorization and assessment of micro-level indicators, we have further explored a large number of indicators, identifying common features, and highlighting particularly relevant correlations between indicators as we cross-reference different classification schemes. We further assessed their characteristics to assist companies in selecting which micro-indicators to adopt in different stages of their product development processes. Results show an unbalance towards indicators focused on environmental and economic dimensions compared to the social dimension, with indicators that incorporate multiple dimensions associated only to end-of-life management and remanufacturing. We conclude also that most indicators that tackle more than a single dimension of sustainability require collecting external data, and that the measure of circularity for a significant number of them is dependent on external conditions (market and legislation) that go beyond the decisions and strategy of the company. This study will further help in the understanding of the practical application of the micro-indicators as well as their adoption by industry, which will promote the transition to a more circular economy.

1. Introduction

The demand for conservation of resources leading to a more sustainable planet, through appropriate waste management methods, has been pushing production systems to a circular economy (CE) model. Companies and governments will be pressed to work together to change the way how society manufactures, uses and discards products, reducing the use of harmful substances and waste generation to reduce (and hopefully minimize) the environmental impact (European Commission, 2018; European Parlament, 2019; Getor et al., 2020; Huysman et al., 2017; Stichnothe and Azapagic, 2013; Zhang et al., 2020).

To reach a more circular economy, it is necessary to “close the loop” of materials life as far as possible. There are obvious – and much necessary – policies that entirely avoid the creation of unnecessary

Abbreviations: CC, Circularity Calculator; CDG, Circularity Design Guidelines; CE, Circular Economy; CEI, Circular Economy Index; CEIP, Circular Economy Indicator Prototype; CEPI, Circular Economy Performance indicator; CI, Circularity Index; CM, Combination Matrix; CPI, Circularity Potential Indicators; DEI, Disassembly Effort Index; DSTR, Decision Support Tool for Remanufacturing; eDIM, Ease of Disassembly Metric; EDT, Effective Disassembly Time; EEI, Economic-environmental indicators; EEVC, Eco-efficient Value Creation; EOL, End of life; EOLI, End-of-life Index; EOLI-DM, End-of-life Indices (Design Methodology); EOL-RRS, End-of-life recycling rates; EPVR, End-of-use product value recovery; EVR, Eco-cost /value Creation; EZWP, Model of Expanded Zero Waste Practice; IOBS, Input-output balance sheet; LCA, Life Cycle Assessment; LI, Longevity Indicator; MCI, Material Circularity Indicator; MRS, Material Reutilization Score; OCDE, Organization for Economic Co-operation and Development; PLCM, Product-level Circularity Metric; PR-MCDT, Product Recovery Multi-criteria Decision Tool; RDI, Recycling Desirability Index; REPRO2, Remanufacturing Product Profiles; RI, Recycling Indices; RPI, Reuse Potential Indicator; SCI, Sustainable Circular index; SDEO, Sustainable design and end-of-life options; SICE, Sustainability indicators in Circular Economy; S-LCA, Social Life Cycle Assessment; TPQ, Typology for Quality Properties; VRE, Value-Based Resource Efficiency.

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waste, such as rethinking and reducing, and which can be coupled with technological advances to avoid waste created during manufacturing and distribution of goods. However, it is equally necessary to find methodologies that help close the loop by recovering post-consumer waste, for example recycling it so it can be fed again into the system to produce new parts, in substitution of continuous use of virgin materials (Getor et al., 2020; Hahladakis and Iacovidou, 2019; Zarbà et al., 2021).

With the transition from a linear to a more circular economic model, the necessity arises of tools that monitor the effect of adopted changes, as well as tools which can help in decision making (Hamam et al., 2021; Reich et al., 2023). In this context, circularity indicators were proposed as tools to measure progress towards a more circular economy, and several authors mention indicators as fairly simple tools (Almeida et al., 2020; Madruga and Rodrigues, 2020; Lonca et al., 2020; Saidani et al., 2019). However, as our analysis illustrates, many indicators are far from simple and their use in a practical context is often prone to subjective interpretation of data as well as requiring extensive collection of information which is not always readily available. An indicator, according to OCDE (Organization for Economic Co-operation and Development), is a quantitative or qualitative variable that provides simply and reliably to measure our achievements, to reflect on changes related to the intervention or to help assess the performance of a developing actor (Almeida et al., 2020). The purpose of circularity indicators is to evaluate different aspects of industrial activities, compliance to regulation and norms, identify patterns along time, help decision makers select among different suppliers and available technologies, inform society at large of circular economy progress, and evaluate the application of scientific research developments (Almeida et al., 2020). Thus, indicators need to be easy to apply to industrial practice (Feil et al., 2015), making it vital to provide as many guidelines and information as possible to companies wanting to have a quick measure of circularity.

One of the barriers identified in the literature (Elia et al., 2017; Saidani et al., 2017; Van Hoof et al., 2018)is the lack of indicators that quantify the circularity at the micro-level (individual products and services), which is particularly paramount for both developers and consumers. Since 2016 an increase was observed in the scientific literature in the scope of micro-level circularity indicators, reflecting an awareness of the significant need to evaluate and document the progress towards a more circular economy with respect to organizations and products (De Pascale et al., 2021; Kristensen and Mosgaard, 2020). With this surge of different micro-level circularity indicators, it has since been claimed that sufficient indicators are now available and that “previous statements advancing that few C-indicators are situated at the micro-level of the CE are somehow no longer true” (Saidani et al., 2019).

However, there is no common ground to these micro indicators, and most of them evaluate circularity through “take-back” processes, such as remanufacturing or recycling EOL products. Much less importance is given to eco-design tools and promoting product life extension, through reuse or recondition. Note that at the time of this study, reuse is understood as a product recovered at the end of its use cycle and given a new use cycle without requiring a significant technical operational of remanufacturing, for example, only by proper cleaning or replacement of consumable or fast-wearing components.

Furthermore, these micro indicators focus on just one CE dimension, leaving out other factors, such as emissions and energy, and few micro indicators provide a holistic approach (Saidani et al., 2019). In some cases, information is difficult to obtain, as for example to characterize the level of maturity of processes for the end-of-life recycling of a certain material, and advanced computational approaches such as data mining (Spreafico and Spreafico, 2021) can prove valuable for decision-makers to retrieve updated information on available technology.

Recently, Kristensen and Mosgaard, 2020 reviewed a set of circularity micro indicators with relevance in scientific literature. The micro indicators resulted from this review were categorized into three types, such as quantitative indicators, analytical tools, and composites indicators. Furthermore, the authors mapped these micro indicators in nine CE categories (according to their main focus) and in three sustainability dimensions (according to the dimensions of sustainability in the measurement of circularity). To complement that assessment and categorization, we have performed a detailed analysis of the different circularity micro indicators and identified patterns which can be useful in applying the indicators to practical cases.

While many micro-level circularity indicators have been reported in the literature in recent years, and we have identified over 100 such indicators mentioned in 11 literature review papers (see Corona et al., 2019; de Oliveira et al., 2021; De Pascale et al., 2021; Elia et al., 2017; Jerome et al., 2022; Kristensen and Mosgaard, 2020; Lindgreen et al., 2020; Moraga et al., 2019; Rossi et al., 2020; Saidani et al., 2019; Sassanelli et al., 2019; and references within), we concluded the work by Kristensen and Mosgaard is still the most extensive and rigorous categorization attempt done on micro-level indicators. Out of the 30 indicators considered by Kristensen and Mosgaard, 15 of them are featured in the majority of the aforementioned 11 review papers, and the other half are featured in at least some of those review papers. Only 7 indicators that are cited in the majority of those review papers were not considered by Kristensen and Mosgaard, and they are cited in Table A.1 in Appendix A. As it would not be feasible to establish proper correlation between those 7 indicators and the features that led to the categorization in (Kristensen and Mosgaard, 2020), we decided to focus our current work on the 30 indicators that were considered by Kristensen and Mosgaard. In future work, we aim to further expand our study to additional indicators, given that some are relevant in specific aspects of circular economy.

It should be pointed out that in order to gather information from the literature on existing micro-indicators, their purpose/approach, and their use, we started with a general literature search with keyworks that included ‘indicator’ and ‘circularity’ and ‘micro’ and ‘product’. We focused on review papers, as these collect information from multiple individual sources in a structured way. From those review papers, we then analyzed the listed references to identify the proper source for each indicator mentioned in the literature. We then analyzed all the individual sources to ensure we had a complete and accurate overview of existing micro-level indicators.

Micro indicators can be a valuable tool for companies when used as a decision factor in acquisitions, design, end-of-life options, or takeback processes. However, unlike what is often postulated by the creators of the indicators, most are not easy to employ. And while the categorization by Kristensen and Mosgaard was very relevant, it does not help understand each indicator or its key characteristics. Furthermore, that categorization does not highlight the distribution of indicators among different dimensions or bring up some common features and trends. It also does not help researchers or companies decide which indicators to use depending on what are their key concerns in terms of circular economy or depending on who will be performing the analysis (and at what stage of the product development cycle it will be used). Our practical work with applying indicators to different industrial case studies led us to realize there are such features, and that when the indicators are analyzed, relevant new information emerges compared to that reported in (Kristensen and Mosgaard, 2020).

As such, our work aims at facilitating the practical adoption of indicators by companies. Since legislation is starting to require companies to share responsibility for the entire life cycle of their products (de Oliveira et al., 2021), including tracking the post-consumer stage, we consider the practical application of micro-level indicators implies companies understand how much influence their internal strategic decisions have on each indicator. Given the fact companies will be sharing results of indicators with other entities, it is equally important for them to know which indicators they can calculate with information at hand, versus those which require obtaining external information. Last, since the design stage significantly influences the impact of the entire life cycle of a product (de Oliveira et al., 2021), it is vital for companies to understand which indicators are most useful at the early design stages, providing useful guidelines to product development teams.

In search of existing patterns, we carried out several other comparative assessments and classifications, expanding into several new directions the work done by Kristensen and Mosgaard. Fig. 1 schematically presents the relevant analysis methodology performed in this paper, which are discussed in detail in subsequent sections. Note that aside from the analyses described herewith, we have also attempted to establish other comparisons among the 6 characteristics listed in Fig. 1, but for many we have found no relevant correlations, and thus decided not to include them in this paper. We concluded there were 5 main analyses that yield novel information compared to the initial framework proposed by Kristensen and Mosgaard. These analyses are discussed in Section 3.

The paper is structured as follows: in Section 2 we describe and characterize the review of micro level indicators for circular economic, namely purpose and quantification methodology, initially based on the classification work by Kristensen and Mosgaard. In Section 3, we present our own mapping of the indicators based on a number of dimensions, and we discuss comparative analyses where we have identified interesting patterns among indicators. Finally, some conclusions are drawn in Section 4.

2. Literature review

A circularity micro indicator is a metric or formula that qualifies or quantifies, respectively, the linear economy transition to a circular economy (Kristensen and Mosgaard, 2020). To measure this transition for companies or products, circularity micro indicators are a valuable tool, allowing strategic decision support about design, production, and end-of-life management. They can be used in combination or alternatively to other metrics and methods, such as Life Cycle Assessment (LCA), which capture different aspects of sustainability and circularity (Vadouvi et al., 2022).

Among the 30 micro indicators identified by Kristensen and Mosgaard (2020), we have concluded 28 micro indicators continue relevant in the scientific literature and our work focused on those 28 (the other 2 included an online tool and a model for which we could not find a proper source documenting and supporting it). The extensive list of source references with definitions of these micro-indicators are summarized in Table A.2 in Appendix A. Given that many of the full names of the micro-indicators are quite extensive, we shall use in the discussions only their acronyms.

2.1. Micro circularity indicators

The micro circularity indicators present in literature are divided into three types, according to Kristensen and Mosgaard (2020). These types are quantitative indicators, analytical tools, and composite indicators. Quantitative indicators present circularity through a single number. The analytical tools categorize circularity through guidelines, tools, or models, and give a qualitative assessment. Composite indicators combine quantitative indicators and analytical tools to evaluate circularity of products or companies.

Some quantitative indicators require the weight of the product or components (i.e., Recycling Desirability Index (RDI) (Mohamed Sultan et al., 2017), Circular Economy Index (CEI) (Di Maio and Rem, 2015), and Material Circularity Indicator (MCI) (Ellen MacArthur Foudation and ANSYS Granta, 2019)), or are dependent on the recycled / recovered / biologic resource content (i.e., MCI, Material Reutilization Score (MRS) (CradletoCradle, 2016), Longevity Indicator (LI) (Franklin-Johnson et al., 2016)). Others are dependent on the generated waste versus resources obtained by recovery techniques (i.e., MCI, Reuse Potential Indicator (RPI) (Park and Chertow, 2014), and LI). The rest of the indicators consider the virgin or recycled feedstock value/cost (i.e., CEI, Eco-cost /value Creation (EVR) (Vogtländer et al., 2013), and Value-Based Resource Efficiency (VRE) (Di Maio et al., 2017)). Only two of the indicators consider the numbers of parts, fastener types, and the necessary tools to disassemble the product in estimating circularity by calculating the time required for disassembly (i.e., Effective Disassembly Time (EDT) (Mandolini et al., 2018) and Ease of Disassembly Metric (eDIM) (Vanegas et al., 2018)). Only the LI focuses on the lifetime of the product. Most analytical tools calculate circularity by considering the value of materials or components, cost of the recovery process, cost of the disassembly process and the social and environmental impacts. The analytical tools include economic dimensions to calculate circularity.

2.2. Main circular economy focus of micro indicators

Kristensen & Mosgaard, in their 2020 paper, categorized each micro indicator in literature according to the main CE focus. This resulted in nine categories, namely: Lifetime extension, Resource Efficiency, EOL (End of Life) management, Waste Management, Recycling, Remanufacturing, Reuse, Disassembly, Multidimensional indicators. The allocation of micro-indicators into the nine CE categories is schematically presented in Fig. 2, which provides a clearer perspective on the distribution of the indicators among the 9 categories. Most of the micro indicators were categorized as having their main in Recycling, Remanufacturing, or EOL Management. Very few (only 2 to 3) of them consider Reuse, Disassembly, Waste Management, Life Extension, or Resource Efficiency (Kristensen and Mosgaard, 2020). It is also clear that micro indicators focused on Disassembly are of narrow scope, while Reutilization is always tackled concomitantly with other categories in the few indicators that consider it. The same can be said of Life Extension, which features 1 very focused indicator, with 2 others that consider multiple aspects simultaneously (recycling plus remanufacturing, or recycling plus waste management).

Although recycling is one of the less sustainable approaches of CE, its

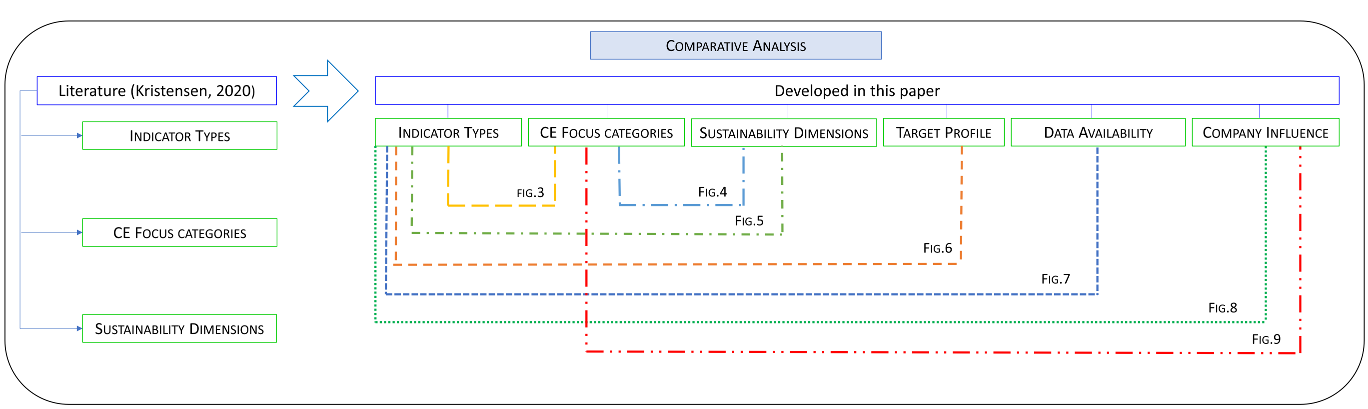

Fig. 1. Schematic of the performed analyses.

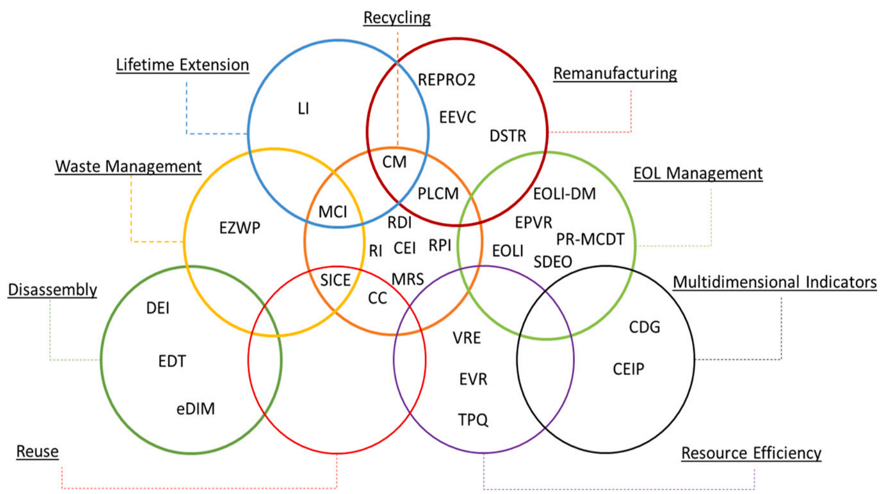

Fig. 2. Micro indicators and their distribution among CE categories (adapted from Kristensen and Mosgaard, 2020). Where, CC-Circularity Calculator, CDG-Circularity Design Guidelines; CEI-Circular Economy Index, CEIP - Circular Economy Indicator Prototype, CEPI-Circular Economy Performance indicator, CM-Combination Matrix, DEI-Disassembly Effort Index, DSTR-Decision Support Tool for Remanufacturing, eDIM-Ease of Disassembly Metric, EDT-Effective Disassembly Time, EEVC-Eco-efficient Value Creation, EOLI-End-of-life Index, EOLI-DM-End-of-life Indices (Design Methodology), EPVR-End-of-use product value recovery, EVR-Eco-cost /value Creation; EZWP, Model of Expanded Zero Waste Practice; LI, Longevity Indicator; MCI, Material Circularity Indicator, MRS-Material Reutilization Score, PLCM-Product-level Circularity Metric, PR-MCDT-Product Recovery Multi-criteria Decision Tool, RDI-Recycling Desirability Index, REPRO2-Remanufacturing Product Profiles, RI-Recycling Indices, RPI-Reuse Potential Indicator, SCI-Sustainable Circular index, SDEO-Sustainable design and end-of-life options, SICE-Sustainability indicators in Circular Economy, TPQ-Typology for Quality Properties and VRE- Value-Based Resource Efficiency.

use is quite common, as a third of all reviewed micro indicators focuses on this category (De Pascale et al., 2021; Kristensen and Mosgaard, 2020). In fact, 5 micro-indicators, i.e., RDI, Recycling Indices (RI) (Van Schaik and Reuter, 2016), RPI, CEI, and MRS, have recycling as their single CE focus, and 5 micro-indicators, i.e., Combination Matrix (CM) (Figge et al., 2018), Product-level Circularity Metric (PLCM) (Linder et al., 2017), MCI, Sustainability indicators in Circular Economy (SICE) (Mesa et al., 2018), and Circularity Calculator (CC) (IDEAL and CO Explore, 2021), split their focus between Recycling and other categories.

Remanufacturing is a concept more recent than Recycling and includes refurbishment, recondition, and repurpose (Kristensen and Mosgaard, 2020), even those these concepts have slightly different nuances. This category uses components or parts of one product to produce a new product. From the 5 micro indicators focused on Remanufacturing, 3 of them present it as a single CE focus, i.e., Eco-efficient Value Creation (EEVC) (Vogtländer et al., 2013), Remanufacturing Product Profiles (REPRO2) (Zwolinski et al., 2006), and Decision Support Tool for Remanufacturing (DSTR) (van Loon and Van Wassenhove, 2018), while the other 2 split their CE focus with Life extension and Recycling.

The EOL Management is another predominant category. Micro-indicators allocated to this category are based on materials, the cost of different EOL options, i.e., End-of-use product value recovery (EPVR) (Cong et al., 2017), End-of-life Index (EOLI) (Lee et al., 2014), and End-of-life Indices Design Methodology (EOLI-DM) (Favi et al., 2017), and social or environmental influences, i.e., Sustainable design and end-of-life options (SDEO) (Ameli et al., 2019) and Product Recovery Multi-criteria Decision Tool (PR-MDCT) (Alamerew and Brissaud, 2017).

The micro indicators in the Waste Management category consider two different waste management approaches: waste generation through linear material flow, with those micro indicators dividing their focus with Reuse and Life Extension, i.e., SICE and MCI, respectively, and a single focus indicator that considers waste management as the final solution to elimination waste, i.e., Model of Expanded Zero Waste Practice (EZWP) (Veleva et al., 2017).

Very similarly, the Life Extension category considers increasing the lifetime of products through design strategies and business models, featuring a single focus indicator, i.e., LI, and 2 indicators dividing their focus with Waste Management and Recycling, i.e., MCI and CM, respectively.

Reuse is a relatively newer CE strategy in the area of sustainability and is hierarchically higher than more traditional ones such as recycling or remanufacturing. However, while reuse can be a viable model for some services, its implementation in industry is hampered as it does not fit to traditional industrial production practices and strategies.

Disassembly is a key strategy to ensure the maximum potential of CE strategies such as remanufacturing and recycling. In the literature we found 3 indicators with a single CE focus in disassembly. These are generally measured in time or value, qualitatively assessing the disassembly sequence, the product architecture, and eventually necessary tools.

In the Resource Efficiency category all micro indicators are of single focus and evaluate in terms of qualitative indices, i.e., EVR, VRE, Typology for Quality Properties (TPQ) (Lacovidou et al., 2019).

Last, the multidimensional indicators consider multiple categories and strategies of CE and feature 2 micro indicators, i.e., Circularity Design Guidelines (CDG) (Bovea and Pérez-Belis, 2018), and Circular Economy Indicator Prototype (CEIP) (Cayzer et al., 2017). Only 3 categories, namely Disassembly, Resource Efficiency, and Multidimensional Indicators, contain only single focus indicators.

It should be noted that before classifying micro indicators per type and CE categories, Kristensen and Mosgaard (2020) studied the inclusion of sustainability dimensions in the circularity calculation methodology for each micro-indicator. Follow-up studies published by De Pascale et al. (2021) and de Oliveira et al. (2021), also looks at the sustainability dimensions, but widening the scope of analysis to indicators at several levels (micro, *meso*, and macro). In the present paper, we consider the categorization proposed by these authors, but correlated to other features of the micro-indicators.

3. Methodology

In this section, we describe comparative analyses performed to identify relevant patterns among micro indicators and their classifications. As mentioned before and illustrated in Fig. 1, we have concluded the most interesting patterns occur when contrasting the categorization of micro indicators per type with their distribution in CE focus categories, sustainability dimensions, target profile, data availability, and company influence. These 5 analyses are described in the subsequent sections.

The first analysis looks at the distribution of micro-level indicators among the 9 CE focus categories, from which mapping can be clearly observed how some aspects of circular economy have attracted much more attention by authors than others. The second analysis is focused on the distribution in terms of the 3 dimensions of circularity of both the type of indicators and the CE focus categories, highlighting in both cases the significant asymmetric nature of the indicators' distribution. The third analysis looks into the indicator target profile, meaning, who the micro indicator is aimed in its application (e.g., if aimed at evaluating a product, informing a company on the level of circularity, or on the designers so they can make decisions during early design phases). The fourth analysis look into whether the calculation requires data, which is available only internally, only externally, or partially externally to the company (which ties into how accessible the information is expected to be). The fifth analysis evaluates the degree of influence or control which the company has over the parameters driving that micro indicator, meaning, if the company is able to make changes that will affect the circularity or if that measure of circularity is also significantly - and directly - influenced by external factors such as the market or legislation.

4. Results

4.1. Evaluation of circular economy focus

The previously described 9 CE focus categories vary significantly in scope. As such, it is not surprising that some categories feature many more micro indicators than others. This reflects the parameters which currently are more prominent in both the social and the scientific communities, as well as the degree of concern by companies in terms of legislation and certifications. Similarly, some aspects of circularity are more (or even only) relevant when addressed quantitatively, while others can only be evaluated qualitatively (or it suffices for the intended purpose). Thus, in Fig. 3 we illustrate the results of the comparative analysis of the distribution of micro-indicators per types versus their CE focus category.

From the analysis of Fig. 3 we find that the largest category, Recycling, predominantly features quantitative indicators. Thus, not only is Recycling the category attracting the highest interest in terms of estimating circularity, with twice the number of micro indicators of any other category (and there are two categories with 5 micro indicators), but their calculation is numeric. In fact, these micro-indicators use parameters such as the weight of components/products, amount of waste collected for recycling, content of recycled materials incorporated in new products, and waste generation fraction that goes into the recycling process.

Interestingly, while Waste Management features only 3 micro indicators, only the Waste Management and the Recycling categories contain the three types of micro indicators (quantitative, analytical, and composite). Among the micro indicators allocated to Recycling, all types of recycling are considered: mechanical, pyrolysis, solvolysis, and composting. On the other hand, micro indicators focused on Waste Management consider the amount of unrecovered material from recycling or disposal in a landfill and the amount of recovered energy by incineration. Eventually, as these two categories are quite mature among CE waste reduction strategies, that may justify the various types of available indicators.

The Remanufacturing, Reuse, EoL Management, and Multidimensional Indicators categories feature only analytical tools and composites indicators. These CE categories are much more recent, and thus likely less studied in terms of quantifying circularity. Micro indicators focused on these categories calculate circularity considering the product's material/components/ composition, the compliance level to eco-design guidelines, and materials recovered on EoL options, and are assessed mainly through analytical tools.

Conversely, the Disassembly and Life Extension categories feature only quantitative and composite indicators, with a prevalence of quantitative indicators. This fact may be justified by these CE categories measuring circularity considering the time factor (disassembly time or lifetime brought to the product through recovery processes). Thus, these CE categories are linked by common factors, namely the easier and faster the disassembly process, the easier it will be to recover, reuse, or refurbish the product's components, thus extending their lifetime.

4.2. Evaluation of sustainability dimensions

When analyzing the relation between the different types of indicators and their focus in terms of sustainability dimensions, we find a significant asymmetry. As represented in Fig. 4, we find quantitative indicators concerned either with the environmental or the economic dimension (in similar numbers, and only 1 of them bridging the two dimensions), but none related to the social dimension. In fact, the lack of micro-indicators in the literature that either focus or at least partially contemplate the social dimension is somewhat surprising, but we associate this effect to two aspects. First, the lack of consensus in defining and qualifying or quantifying the social dimension, which is corroborated by the findings of (de Oliveira et al., 2021), and which is equally observed in a different area, Life Cycle Assessment (LCA) versus Social Life Cycle Assessment (S-LCA) (Lindgreen et al., 2020). Second, the (understandable) higher concern of micro-indicators with technical aspects of product or the production/distribution/takeback/collection processes, easily noticed when analyzing the calculation/determination method for each micro-indicator, and which de Pascale and Co-authors have also identified (De Pascale et al., 2021).

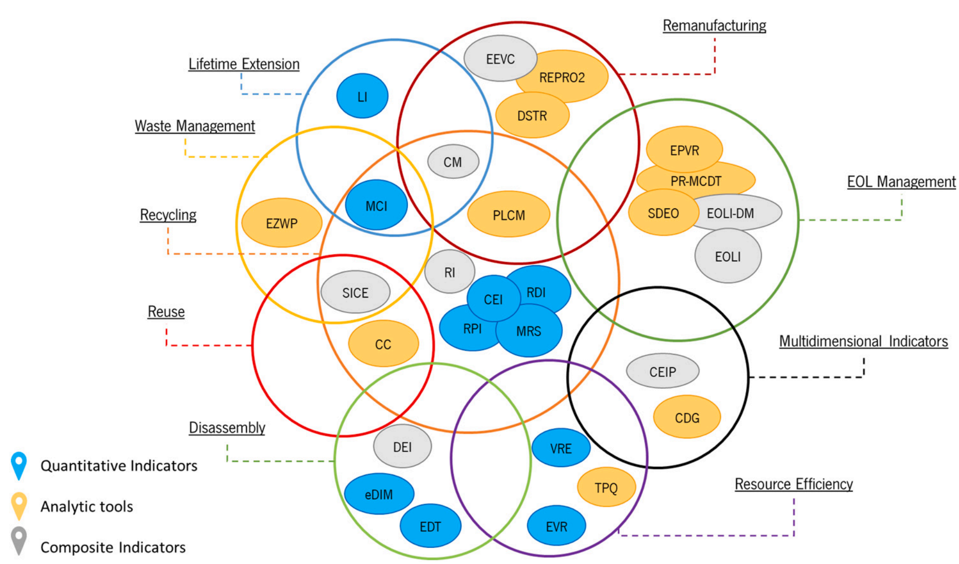

Fig. 3. Cross-reference between categories CE focus and micro indicator types (based on data from Kristensen and Mosgaard, 2020).

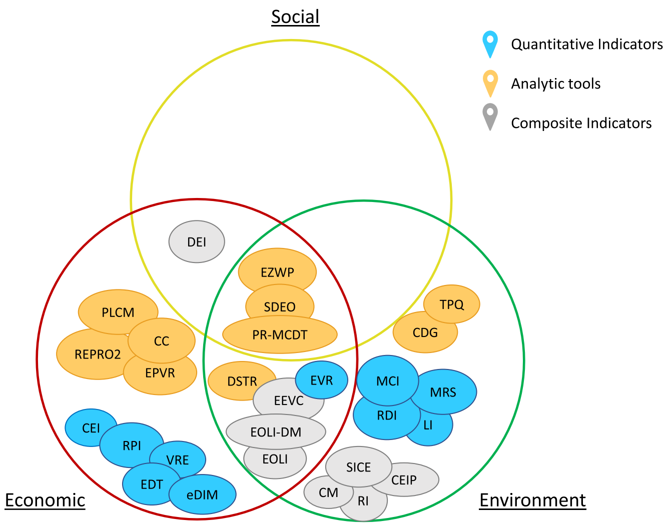

Fig. 4. Cross-reference between sustainability dimensions and micro indicator types (based on data from Kristensen and Mosgaard, 2020).

Analytical tools tend to be more prominently on the economic dimension, although some are focused on the environmental dimension, and 3 micro-indicators of this type are actually the only that consider simultaneously all three dimensions of sustainability. Thus, EZWP, SDEO, and PR-MCDT are tools where information from all three dimensions of sustainability is taken into account, and thus represent a much more holistic perspective than most other micro-indicators.

Composite indicators, on the other hand, are quite focused on the environmental dimension, with a third of them bridging between environment and economic dimensions of sustainability.

It is equally interesting to analyze the sustainability dimensions of each micro-indicator but in terms of their classification in CE focus categories, as presented in Fig. 5.

The recycling category is the largest, yet all its micro-indicators focus on a single dimension of sustainability. And in fact, 6 of those micro-indicators consider only the environmental dimension, and only 4 micro-indicators in this category consider the economic dimension. The latter 2 micro-indicators include factors such as recycled material content, amount of waste collection and recycling, and the environmental impact of the recycling process. Another CE focus category where the micro-indicators are all focused on a single dimension is Life Extension, but in this case, all indicators consider only the environmental dimension.

Two CE categories which are related to each other are Waste Management and EOL Management, both very focused on what happens at the end of life of the product, and it is only in these categories that we find holistic indicators incorporating all three dimensions of sustainability (namely, EZWP, SDEO, and PR-MCDT). We had previously observed these 3 micro-indicators are analytical tools. In the case of EZWP, it considers factors related to the environmental impact, the value or cost involved in waste reduction, and the employee's training and satisfaction in each option of waste reduction. In the case of SDEO and PR-MCDT, they consider factors related to the end-of-life process cost, its environmental impact, and number of employees involved in the process. In fact, the EOL Management category is the most pluridimensional category, featuring also 2 micro-indicators bridging between the environmental and economic dimensions, more precisely EOLI and EOLI-DM which consider factors related to the environmental impact of end-of-life options, costs of end-of-life options, and the value of recovered materials. Curiously, the so-called 'Multidimensional indicators' are in fact focused on a single dimension of sustainability.

The graphical representation that we created through Figs. 3 to 5, based on the reference categorization scheme of (Kristensen and Mosgaard, 2020), allows a much clearer understanding of convergence and clustering of the micro-level indicators within the CE focus categories and the sustainability dimensions. In this way, we extract a plethora of additional information compared to what a simple tabular view allows.

4.3. Evaluation of target profile

In this section we present an analysis of the target profile for each micro-indicator. Namely, we highlight the micro-indicators that are (typically) of major importance to the product development team, at an early design stage, thus supporting decision making at this critical phase by allowing more informed decisions about circularity and sustainability

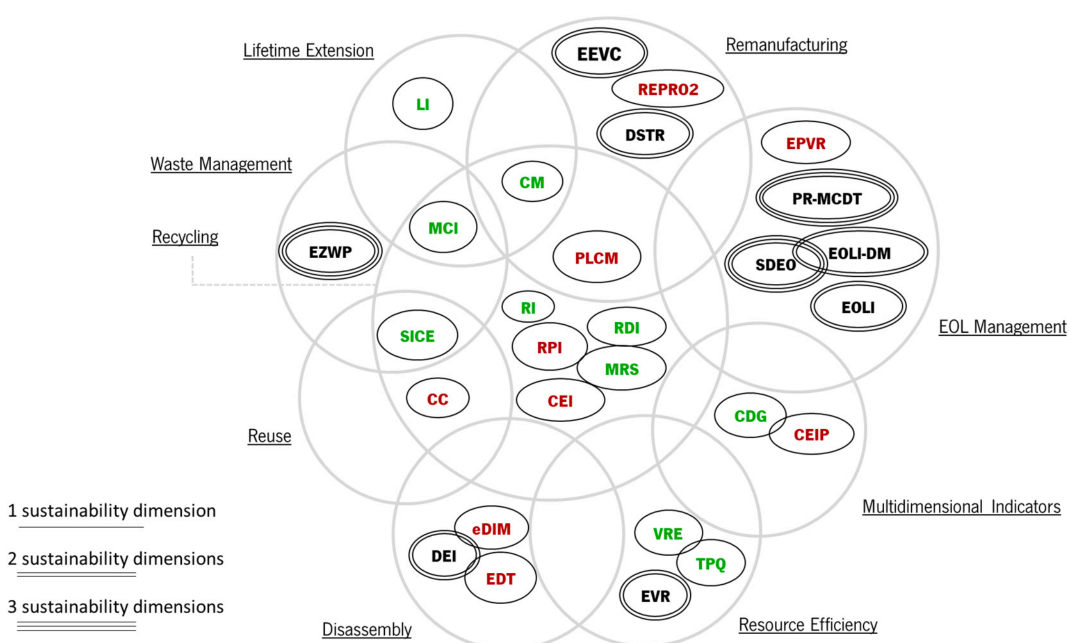

Fig. 5. Cross-reference between sustainability dimensions and CE focus categories (based on data from Kristensen and Mosgaard, 2020). Indicators with text in green consider only the environmental dimension. Indicators with text in red consider only the economic dimension. No indicators consider only the social dimension.

aspects of the product. As is widely known, decisions made at the design stage affect significantly the life cycle of a product, and it is often said that 70–80 % of a product's impacts are influenced during the early design process (Ramani et al., 2010; Rebitze et al., 2003; Simões et al., 2013). The parameters in such selected indicators include product geometry, product architecture, product mass, materials and material source, assembly and disassembly solution and/or sequence and required time, costs of materials and of different EOL options, among others.

The criteria we used to select those micro-indicators were two-fold: all the parameters used in the calculation of a micro-indicator need to be available to the development team (meaning, either the parameter is a decision of the team itself or can be easily procured by the team), and does not require making entirely arbitrary assumptions (since, obviously, any indicator could be calculated even at the early design stage by assuming scenarios, but for some, such scenarios have absolutely no forecast significance). Any micro-indicator that either requires specific values that result from the deployment and post-market stages (e.g. how many of the produced parts are actually retrieved by a takeback system, or how many collected parts can be reused, or how many components need to be replaced to refurbish a part and the respective cost), will be considered external to the product development team, meaning, the team will probably not benefit from projecting scenarios based on such micro-indicator, and usually it should be calculated later by other personnel at the company (e.g. quality control, global company indicators, etc.) once the entire life cycle of the product can be evaluated. In the selection we procured input from the coordinators of 3 product development teams in our network of partners. The result of this analysis is represented in Fig. 6.

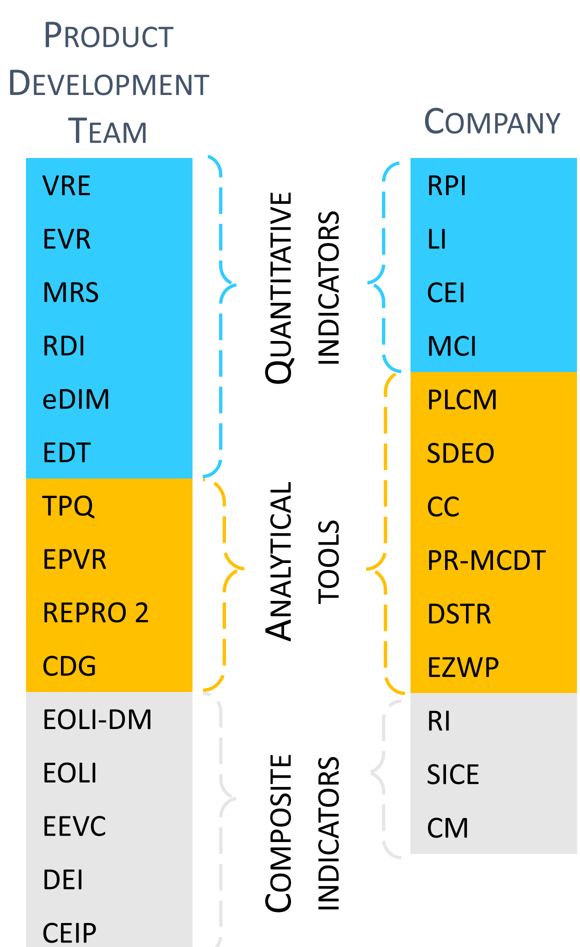

Fig. 6. Comparative analysis between micro-indicator target profile and indicator type.

We have found that more than half of the analyzed micro-indicators are possible to evaluate at an early product development stage, and thus can be part of the work of a product development team that wants to take into account the entire life cycle of the product and to consider sustainable options. Within the highlighted set of indicators, all 3 types are represented. Among quantitative indicators, a little more than half are within reach of the product development team while, conversely, in terms of analytical tools it's a little less than half. As several composite indicators (e.g., EOLI, EOLI-DM, EEVC) are based on analytical indicators, most of these can also be calculated by the product development team.

Naturally, the specific indicators relevant in each case depend on the specific product under development, as depending on its degree of complexity, required processes, feasibility of takeback systems, and other factors, the development team must judge which indicators to use among the ones that have been identified as possible. The calculation of the indicators at this stage will not only provide helpful input about decisions that have to be made at an early design stage but can help the team prepare and better support the product documentation for internal validation by the company decision makers on the go / no-go of the product. If we compare the results in Figs. 4 and 6, we find that among the indicators the product development team should be able to calculate, we find several covering both environmental and economic dimensions, while the few indicators that have a social dimension are outside of the scope of what a product development team would typically be able to determine at this stage.

4.4. Evaluation of data availability

A very important aspect of micro-indicators is the availability of the data required to calculate circularity. As such, we have classified each indicator in terms of whether that data should be readily available internally to the company, whether part of the required data must be obtained from outside sources, or whether it is entirely dependent on data that must be collected from external sources.

Data which should be readily available inside the company includes factors such as product weight, the number of components, or the content of recycled material. Data which requires external sources includes factors such as recovery processes, disassembly operations, or recycling. The comparative analysis between indicator types and data availability is represented in Fig. 7.

Analyzing the results, almost all quantitative indicators are at least – if not entirely – dependent on external data. In order to calculate circularity, they depend on information on the recovery processes (disassembly, remanufacturing, or recycling), economic values (RPI, VRE), or information on recycled or unrecovered materials percentages (RDI, MCI, MRS, LI), which require interfacing with recycling companies and EOL treatment plants. On the other hand, a little more than half the analytical tools depend only on internal data because they are based on the product's weight, material, or recycled content. This relates to the fact that these indicators are mostly tools providing guidelines to improve the product's circularity and do not quantify the circularity level.

If we now cross the results obtained in the analysis of sustainability dimensions and the analysis of data availability, as presented in Fig. 8, we conclude that micro-indicators focused on more than a single sustainability dimension end up requiring external data, which is reasonable considering these indicators incorporate more diverse factors and thus a wider range of inputs. Among the micro-indicators that consider only the environmental dimension, about half requires only internal data while the other half depends partially on external data. The exact same pattern is found for the micro-indicators that consider only the economic dimension.

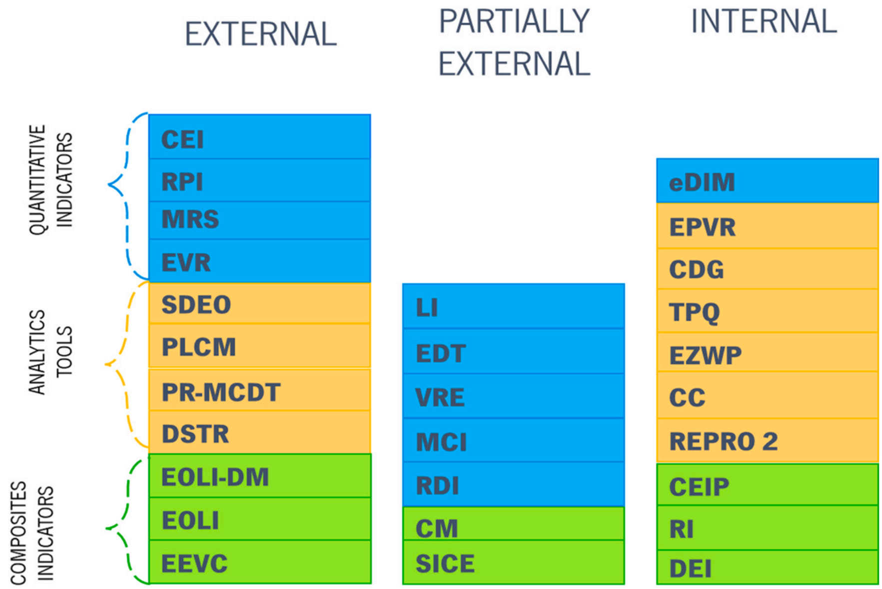

Fig. 7. Availability of data required to calculate each micro-indicator.

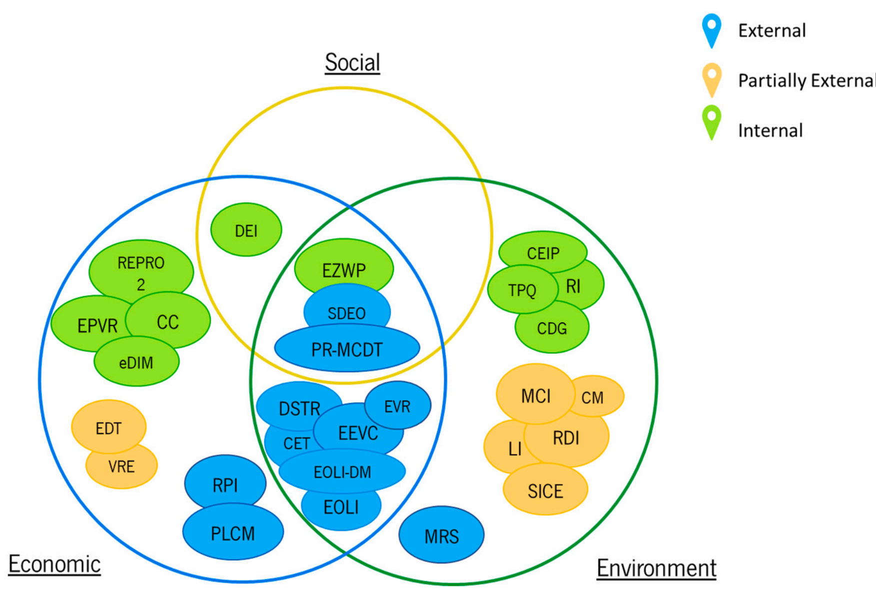

Fig. 8. Comparison of the sustainability dimensions considered in each micro-indicator versus the availability of data required for its calculation.

4.5. Evaluation of company influence

Finally, we evaluate whether each micro-indicator is entirely within the sphere of influence of the company, meaning, if the company has control over all decisions which affect the calculation of the indicator, or whether some factors are controlled by the market or legislation (and thus, despite the company's strategy and vision, can only be partially affected by the company).

Any micro-indicators including factors that depend on the cost or value of raw-materials or cost of production or EOL processes, or distribution costs to estimate circularity are considered as dependent on the market. If they depend on the amount of incorporated recycled material (often imposed by certification or normative regulation) or amount of recycled waste are considered as dependent on legislation. The obtained results are shown in Fig. 9.

We find that, not surprisingly, all micro-indicators are at least partially affected by company decisions. However, few micro-indicators (8 out of 28) are entirely within the sphere of influence of the company, and the same number of indicators are simultaneously dependent on company decisions, market evolution, and imposed legislation. A little more than half the indicators (18 out of 28) are influenced by the market, and about a third of them (10 out of 28) by legislation. Also, the observed patterns are irrespective of the type of indicator, and are analogous for quantitative indicators, analytical tools, and composite indicators.

From a different perspective, we can look at what kind of factors (again, considering ‘Company’, ‘Market’ and ‘Legislation’) influence the micro-indicator calculation when clustering them in the 9 CE focus categories. This analysis is shown in Fig. A.1 in Appendix A. This figure allows us to simultaneously observe the number of indicators in each category (size of the bar), and the factors affecting their calculation (both which they are and their relative proportion).

All micro-indicators in two categories, Disassembly and Multidimensional Indicators, are dependent only on company decisions (in fact,

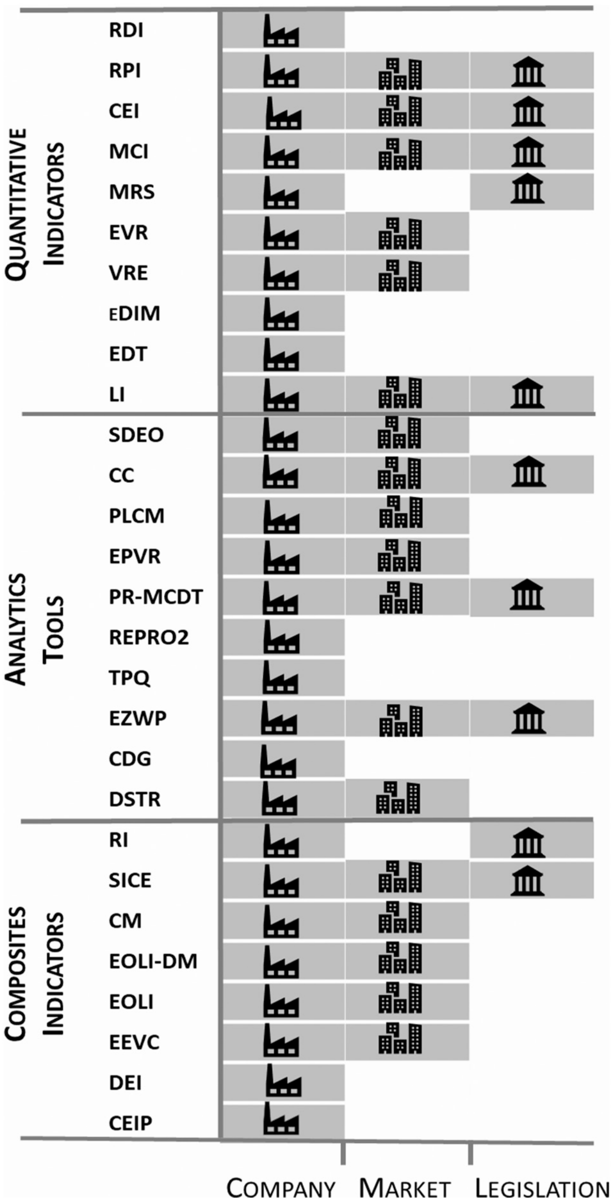

Fig. 9. Comparative analysis considering where is the control over factors that affect the circularity of a product and the types of indicators.

design options), as they consider aspects of the assembly/disassembly process. All micro-indicators in two other categories, Resource Efficiency and the Remanufacturing, are affected both by company decisions as well as the market, as they evaluate the value and cost of materials and remanufacturing process.

Three of the categories, namely Reuse, Life Extension, and Waste Management are influenced in an equal manner by the company, the market, and legislation. Conversely, EOL Management has a small influence from legislation, but is essentially driven by company decisions and market position. Finally, the Recycling category, features micro-indicators that are affected by all 3 factors, although the company has a significant degree of control over most indicators. Being the largest category in terms of micro-indicators means it is also the category which features more indicators affected by legislation, but in terms of proportions, it is akin to other categories.

5. Discussion

Evaluating the comparative analyses that were presented, we can conclude most micro-indicators in the literature to evaluate product circularity are in the Recycling, Remanufacturing, and EOL Management categories, with a strong emphasis on the Recycling category. The indicators in the Recycling category are predominantly (but not exclusively) quantitative in nature, and most of them are focused on a single (in this particular case, the environmental) dimension. Conversely, the indicators in the other 2 mentioned categories, Remanufacturing, and EOL Management, are all either analytical tools or composite indicators, and they tend to be more multi-dimensional in their assessment of sustainability (bridging mostly between the environmental and economic dimensions, but also towards the social dimension). Indicators in the Reuse and the Multidimensional Indicators categories are exclusively analytical tools or composite indicators, such as those in the Recycling and EOL Management categories. However, the remaining categories, Life Extension, Waste Management, Disassembly, and Resource Efficiency, include indicators of multiple types, which means in these categories it is easier to obtain a wider perspective (a more holistic view) on the product, service, or system under study, just like in the Recycling category which features indicators of all types.

When considering sustainability dimensions, it becomes clear from the analysis that very few micro-indicators consider a social perspective in their assessment (only 4 in 28), with about a third of the 28 indicators solely focused on environmental dimension, another third solely on the economic dimension, and another third consider simultaneously both of those dimensions. It is only in the categories of EOL Management and Waste Management (two very related categories) that we find indicators considering simultaneously 3 sustainability dimensions, while those considering simultaneously 2 dimensions are found in several other categories (but, as mentioned before, not in the largest category, Recycling).

A set of indicators are proposed as being particularly targeted to the Product Development Team, as they can be calculated very early in the design process and consider parameters the team should have access to (or be able to confidently estimate). Interestingly, about half of the 28 micro-indicators fall within this concept, while the rest can likely only be calculated at a later stage (often after takeback/remanufacture/repair procedures have taken place during sufficiently long time). Still, there is a myriad of micro-indicators providing very useful decision-making information for the product development team in typical development projects.

On another analysis, almost all quantitative indicators were found to be heavily dependent on data external to the company, while about half analytical tools and composite indicators can be calculated using data immediately available to the company. Almost all indicators that focus simultaneously on 2 sustainability dimensions require external data, but among those that can be calculated only with data available internally, there are indicators dealing with each of the 3 dimensions.

Finally, our analysis shows that only a few micro-indicators are entirely within the sphere of influence of the company, while a little more than half of the 28 micro-indicators in the literature include parameters that are defined by market conditions, and almost a third are also dependent on legislation. Thus, in these cases, irrespectively of the company policy, vision, and sustainability strategies, micro-indicators can only be controlled to a certain extent, and it is important for the company to understand that when estimating circularity or defining internal policy for micro-indicator targets in their products. It was also found that some categories are more prominently affected by the market or legislation. Legislation affects more significantly indicators in the Recycling, Waste Management, Life Extension and Reuse categories. The Market significantly affects indicators in almost all categories with exception of Disassembly and Multidimensional Indicators, categories which are entirely dependent on the company.

This analysis clearly show that beyond classification and

Table 1
Indicator selection practical guidelines.

Indicator selection parameters	Decision criteria	
CE focus category	Single (and which one)	Multiple (and which ones)
Sustainability dimension	Single	Multiple
Product life cycle phase	Development team	Company
Access to data	Internal	External
Control over the indicator	Company	Market/Legislation

categorization of micro-indicators (found in several review papers, e.g. Corona et al., 2019; de Oliveira et al., 2021; Elia et al., 2017; Jerome et al., 2022; Kristensen and Mosgaard, 2020; Lindgreen et al., 2020; Moraga et al., 2019; Rossi et al., 2020; Saidani et al., 2019; Sassanelli et al., 2019), it is also important to understand their practical application and feasibility for industrial implementation, including whether there are other indicators that can provide alternative or complementary insights (within each sustainability dimension), and whether the indicator will support decision making or if it is only for characterizing specific aspects of circularity of a product.

A global summary of the decision criteria that should be taken into account for the selection of indicators is provided in Table 1, and in even more detail for each indicator in Table A.3. These tables facilitate the practical deployment of indicators, as for example someone interested only in more holistic micro-indicators (that consider aspects from multiple categories and multiple dimensions) can immediately limit the range of possible indicators to those that fit these criteria.

6. Concluding remarks

Our work builds upon the categorization conducted by (Kristensen and Mosgaard, 2020) adding several layers of information on the micro-indicators and their practical application. Our graphical representations clearly highlight the asymmetries and the clustering that exist among CE categories and dimensions of sustainability, and call attention to aspects which have received much less attention than others by researchers. We also provide useful guidelines for the selection of micro-indicators by companies, depending on when along the product life cycle stage they will be used, which factors affects them, and which type of information is required for their assessment.

Overall, understanding these different aspects and specific features of micro-indicators is important when using them for establishing sustainability strategies and making design decisions, as micro-level indicators are still considered to be in the maturation stage (Corona et al., 2019; Saidani et al., 2019). This information also helps identify which micro-indicators might be particularly useful to a given product/service/system and allow insights into aspects that may require particular care for the calculation of a given micro-indicator. Last, the provided analysis will hopefully aid companies select which micro-indicators to use among the very large number available in the literature and promote their practical use in industrial settings, which is still lacking (Syu et al., 2022).

The main limitation of the present work is the fact that, given the adopted approach, it was not feasible to compare the micro-indicators included in the categorization and assessment by Kristensen and Mosgaard with the additional indicators we identified outside of their review, as described in the introduction section. In future work, we aim to focus our approach on polymeric materials. While our assessment and categorization of the micro-indicators is applicable to all classes of materials, polymeric materials are of particular interest to the circular economy approach. This is, on the one hand, because they are used in a significant fraction of contemporary society short life span products and their incorrect EOL disposal has a visual impact that creates societal bias against the material itself. On the other hand, plastics have specific recycling processes and technologies (with inherent opportunities and limitations) which distinguish their EOL from that of metals, paper/cardboard, and other classes of materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A.1
Overview of micro-level Circularity indicators not included in the study of Kristensen and Mosgaard.

Name	Description	Principle	Author
SCI	Sustainable Circular index	Degree of sustainability and circularity of company.	(Azevedo et al., 2017)
CEPI	Circular Economy Performance indicator	Quantify the circular economy performance of different waste treatment options.	(Huysman et al., 2017)
CPI	Circularity Potential Indicators	Measuring product performance in a context of circular economy	(Saidani et al., 2017)
EOL-RRs	End-of-life recycling rates	Measuring the amount of material that is collected but lost for downcycling in a product.	(Graedel et al., 2011)
IOBS	Input-output balance sheet	Measures the economic circularity of the resources used in a product, from the installation and maintenance phase to its disposal.	(Capellinni, 2015)
EEI	Economic-environmental indicators	Measuring the environmental and economic impacts through the Global Cost method.	(Fregonara et al., 2017)
CI	Circularity Index	Measuring the circularity of the material trough the losses in quantity and quality when reprocessing the material.	(Cullen, 2017)

Table A.2
Overview of micro indicators present in study (adapted from: Kristensen and Mosgaard, 2020).

Name	Description	Principle	Author
RDI	Recycling Desirability Index	How desirable recycling is.	(Mohamed Sultan et al., 2017)
RPI	Reuse Potential Indicator	How similar a recovered material is to a resource or waste.	(Park and Chertow, 2014)
CEI	Circular Economy Index	Economic value of the materials of end-of-life products.	(Di Maio and Rem, 2015)
MCI	Material Circularity Indicator	Degree of circularity of a product based on the flow of its materials.	(Ellen MacArthur Foundation, 2019)
MRS	Material Reutilization Score	Score the product according to its fraction of recyclable material.	(CradletoCradle, 2016)
EVR	Eco-cost /value Creation	Efficiency of resources by the ratio between eco costs and the value of a product.	(Vogtländer et al., 2013)
VRE	Value-Based Resource Efficiency	Resource efficiency based on mass and in line with environmental/social/economic policies.	(Di Maio et al., 2017)
eDIM	Ease of Disassembly Metric	Disassembly time for a product.	(Vanegas et al., 2018)
EDT	Effective Disassembly Time	Effective time to disassemble a product to isolate a target component.	(Mandolini et al., 2018)
LI	Longevity Indicator	Period that a material is retained in a product cycle.	(Franklin-Johnson et al., 2016)
PLCM	Product-level Circularity Metric	Based on the economic value of all parts as a basic unit and the product is aggregated in a circular metric.	(Linder et al., 2017)
CC	Circularity Calculator	Recycled content of a product.	(IDEAL, 2021)
EPVR	End-of-use product value recovery	Method with different options for managing end-of-use products.	(Cong et al., 2017)
SDEO	Sustainable design and end-of-life options	Sustainable design performance of an end-of-use product family.	(Ameli et al., 2019)
PR-MCDT	Product Recovery Multi-criteria Decision Tool	Feasibility of selecting remanufacturing as an option to recover an end-of-use product.	(Alamerew and Brissaud, 2017)
REPRO2	Remanufacturing Product Profiles	Tool that assists in the design of remanufactured products, based on eco design proposals.	(Zwolinski et al., 2006)
TPQ	Typology for Quality Properties	Screening tool of the quality of materials/components of a product, to improving resource efficiency	(Lacovidou et al., 2019)
EZWP	Model of Expanded Zero Waste Practice	Starting point for companies to develop indicators for waste management (on a zero-waste approach).	(Veleva et al., 2017)
CDG	Circularity Design Guidelines	Design guidelines for improving product design from a circular economy perspective.	(Bovea and Pérez-Belis, 2018)
DSTR	Decision Support Tool for Remanufacturing	Evaluates whether remanufacturing is an economically and environmentally viable process.	(van Loon and Van Wassenhove, 2018)
RI	Recycling Indices	Sets a product's recycling and recovery rate and assigns an efficiency category to recycling.	(Van Schaik and Reuter, 2016)
SICE	Sustainability indicators in EC	Set of 5 indicators based on the sustainability and functional performance of a product.	(Mesa et al., 2018)
CM	Combination Matrix	Contributes to the circular use of resources in the company.	(Figge et al., 2018)
EOLI	End-of-life Index	Total costs of each end-of-life product management process.	(Lee et al., 2014)
EOLI-DM	End-of-life Indices (Design Methodology)	Total costs of each end-of-life product management process based on eco design methodologies.	(Favi et al., 2017)
EEVC	Eco-efficient Value Creation	Based on the EVR in a model to assess the potential of remanufacturing.	(Vogtländer et al., 2013)
DEI	Disassembly Effort Index	Work and processes required to disassemble a product to provide a score for the product.	(Das et al., 2000)
CEIP	Circular Economy Indicator Prototype	Tool that assesses product performance in the context of the circular economy.	(Cayzer et al., 2017)

Table A.3
Indicator selection practical guidelines, where Rec – Recycling; LE – Life Extension; WM – Waste Management; RE – Resource efficiency; D – Disassembly; Rem – Remanufacture; Reu-Reuse; EOL – End of life management; MI-Multidimensional indicators; Env – Environmental Dimension; Eco – Economic Dimension; Soc – Social Dimension; PD – Product development team; C – Company; I – Internal; E – External; M – Market; L – legislation.

Indicator		Decision Criteria				
		CE Focus Category	Sustainability Dimension	Product life cycle phase	Access to data	Control over the indicator
Quantitative indicators	RDI	Rec	Env	PD	I/E	C
	RPI	Rec	Eco	C	E	C/M/L
	CEI	Rec	Eco	C	E	C/M/L
	MCI	Rec/LE/WM	Env	C	I/E	C/M/L
	MRS	Rec	Env	PD	E	C/L
	EVR	RE	Eco/Env	PD	E	C/M
	VRE	RE	Eco	PD	I/E	C/M
	eDIM	D	Eco	PD	I	C
	EDT	D	Eco	PD	I/E	C
	LI	LE	Env	C	I/E	C/M/L
Analytic tools	PLCM	Rec/Rem/	Eco	C	E	C/M
	CC	Rec/Reu	Eco	C	I	C/M/L
	EPVR	EOL	Eco	PD	I	C/M
	SDEO	EOL	Eco/Env/Soc	C	E	C/M
	PR-MCDT	EOL	Eco/Env/Soc	C	E	C/M/L
	REPRO2	Rem	Eco	PD	I	C
	TPQ	RE	Env	PD	I	C
	EZWP	WM	Eco/Env/Soc	C	I	C/M/L
	CDG	MI	Env	PD	I	C
	DSTR	Rem	Eco/Env	C	E	C/M
Composite indicators	RI	Rec	Env	C	I	C/L
	SICE	Rec/WM/Reu	Env	C	I/E	C/M/L

(continued on next page)

Table A.3 (*continued*)

Indicator	Decision Criteria				
	CE Focus Category	Sustainability Dimension	Product life cycle phase	Access to data	Control over the indicator
CM	Rec/LE/Rem	Env	C	I/E	C/M
EOLI	EOL	Eco/Env	PD	E	C/M
EOLI-DM	EOL	Eco/Env	PD	E	C/M
EEVC	Rem	Eco/Env	PD	E	C/M
DEI	D	Eco/Soc	PD	I	C
CEIP	MI	Env	PD	I	C

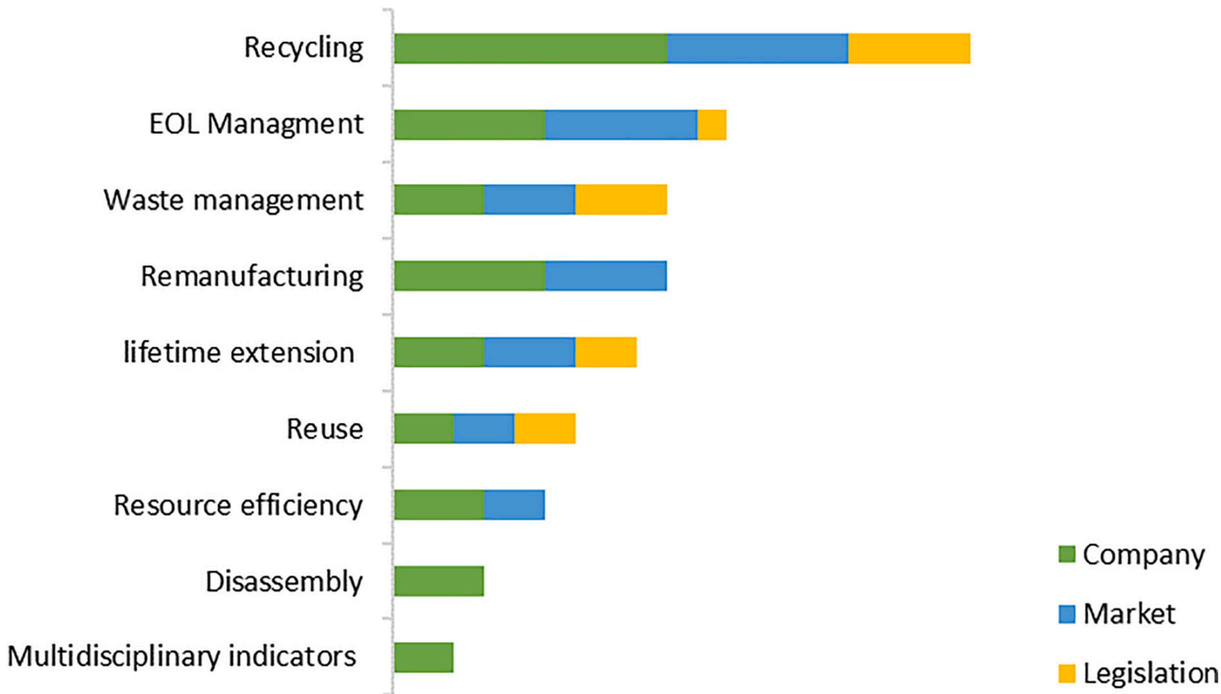

Fig. A.1. Comparative analysis between CE focus category and the control over factors influencing the calculation of circularity of a product.

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