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Circular Economy indicators for supply chains: A systematic literature review

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ABSTRACT

Recently, the Circular Economy paradigm has emerged as an alternative to linear and unsustainable production and consumption systems. However, no established indicator exists to assist the transition of supply chains to a higher degree of circularity; also, most of the literature on Circular Economy indicators has focused on the firm rather than on the supply chain as the level of analysis. Through a Systematic Literature Review, this paper examines decision support tools, and related indicators, employed for assessing the performance of Circular Supply Chains in the academic literature. In parallel, a content analysis and a template technique are employed to evaluate how Multi National Enterprises measure the effect of the adoption of Circular Economy practices in their reports. Results are synthesised in two composite indicators, which aggregate the most commonly employed metrics. Findings show that both academic literature and industrial practice show a scarce consideration of social and circularity measurements, rather focusing on classical environmental impacts and economic ones. In the academic literature, the economic dimension is prevalent; practitioners seem to evaluate and communicate more often the environmental impacts of already adopted Circular Economy practices. This article also recognises the different and sometimes hidden worldview assumptions in current Circular Economy indicators, highlighting that different paths toward Circular Supply Chains are possible depending on value and methodological choices. Future contributions should explicetly state these assumptions and their idea of a Circular Economy.

1. Introduction

Since the first industrial revolution, supply chains have operated according to a linear paradigm, based on the extraction and unsustainable use of natural resources. This has caused irreversible ecological damage, as half of the total greenhouse gas emissions and more than 90% of biodiversity and water losses are related to resource extraction and processing (Bressanelli et al., 2019; Kazemi et al., 2019; European Commission, 2020). The Circular Economy (CE) concept was developed to reverse unsustainable patterns of development and create long-term prosperity (Fitch-Roy et al., 2020). In the CE paradigm, every economic activity should maximise ecosystem functions and human well-being (Murray et al., 2017). As such, the frontiers of environmental sustainability are pushed forward, and products are transformed in such a way that there are workable relationships between ecological systems, economic growth and human well-being. A higher circularity in the use of materials is supposed to provide organisations with a wide range of economic benefits; these include: reduced materials costs, greater value extraction from resources and greater resilience (Rosa et al., 2019), as well as a positive contribution to environment and society as a whole (Chiappetta Jabbour et al., 2019; WBCSD, 2019).

Because of the benefits of circular supply chains (CSCs), companies have recently been placing more emphasis on achieving sustainable production, by shifting from simple mitigation actions to a focus on prevention of environmental damage, based on whole lifecycle assessment and integrated environmental strategies and management systems (Zhu et al., 2011; Larsen et al., 2018). This trend has also become apparent in the academic literature focused on supply chain management (SCM) where many scholars have analysed how to close the loop of products and materials (Govindan and Bouzon, 2018; Lahane et al., 2020). Within the Industrial Ecology (IE) (Helander et al., 2019), Green and Sustainable Supply Chain Management (GSCM and SSCM) (Genovese et al., 2017a) and Closed-Loop Supply Chain Management (CLSCM) streams of literature (Rezaei et al., 2019), decision support tools (DSTs) for designing and assessing CSCs have been proposed (Bressanelli et al., 2019; Kazemi et al., 2019). These DSTs employ several CE indicators to measure the adoption of CE practices towards desired targets (e.g. economic, environmental and social) (Morseletto, 2020).

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It is worth to note that existing reviews of CE indicators show that there is no agreement among researchers and practitioners on what metrics should be selected for the different sustainability pillar and on how to deal with trade-offs (Sassanelli et al., 2019a; Saidani et al., 2019; Vinante et al., 2021). There is no consensus on a set of indicators that should measure desirable levels of circularity and establish improvement pathways for production and consumption systems (Vinante et al., 2021). However, these reviews (Saidani et al., 2019; Sassanelli et al., 2019a; Vinante et al., 2021) focus on indicators and tools at the firm level rather than including existing knowledge and research gaps at the supply chain level.

To fill this gap, this study reviews CE indicators at a supply chain level developed and employed in the academic literature and in industrial practice. This will allow the identification of a subset of frequently employed metrics across all the sustainability pillars and the proposal of two prototypes of composite indicators (CIs). These two CIs select and aggregate the most frequently mentioned metrics in the academic literature and in industrial practice. The review also questions the reductionist nature of the different approaches employed for measuring the performance of supply chains from a CE perspective. It then proposes a set of recommendations aimed at overcoming the limitations of the current literature.

The remainder of this paper is arranged as follows. The next section introduces the research background, defining CSCs and the different approaches that decision support systems can adopt, along with the general sustainability measurement debate. In Section 3, the method utilised to tackle the research questions is illustrated. Firstly, a systematic literature review (SLR) explores DSTs in the context of decision making in CSCs. Secondly, content analysis is used to reveal the CE Indicators in a sample of Corporate Sustainability (CS) Reports from Multi National Enterprises (MNEs). Section 4 shows the results of both analyses, the most frequent metrics in DSTs for CSCs, the type of decision supported, and the type of sustainability dimension considered. Indicator systems are classified in to three groups on the basis of their underlying assumptions; a taxonomy of CE indicators for MNEs is also presented. In Section 5, results are discussed; also, promising future research avenues are proposed. In Section 6, conclusions are drawn, and the limitations of the study are illustrated.

2. Research background

Supply chains and inter-firm relationships have a crucial role in supporting the transition towards a CE (EMAF, 2015; Fischer and Pascucci, 2017; Herczeg et al., 2018). In CSCs (Fig. 1), companies cooperate not only to deliver goods and services to customers, but also to provide feedback loops that allow for methods of production to be self-sustaining and for materials to be used multiple times (Bocken et al., 2013; den Hollander et al., 2017; Webster, 2017). Products are designed to last longer and to flow through multiple use phases (Bovea and Pérez-Belis, 2018; Sassanelli et al., 2020); materials are recovered and recycled (Go et al., 2015; Wahab et al., 2018). A very important role is played by how products and business models are designed (Bocken et al., 2016, 2017; Pigosso and McAloone, 2017; Lüdeke-Freund et al., 2019; Centobelli et al., 2020), with companies providing services and *performances*, rather than just products (Tukker, 2015; Prendeville and Bocken, 2017; Sassanelli et al., 2019b). The result is that each product is considered as an asset, whose value is to be preserved for as long as possible in an attempt to displace (at least partially) the demand for new products and primary materials (Zink and Geyer, 2017; Rocca et al., 2021). This is expected to help keep consumption levels inside planetary boundaries (Rockström et al., 2009). A CSC should be able to:

- Coordinate forward and reverse logistics supporting the creation of value from circular and product-as-a-service business models (Batista et al., 2018; Ebikake et al., 2018);
- Reduce (ideally, to zero) waste streams, by systematically restoring technical materials and regenerating biological materials (Farooque et al., 2019);
- Limit the throughput flow of societal systems to a level that nature tolerates, and utilise ecosystem cycles in economic cycles by

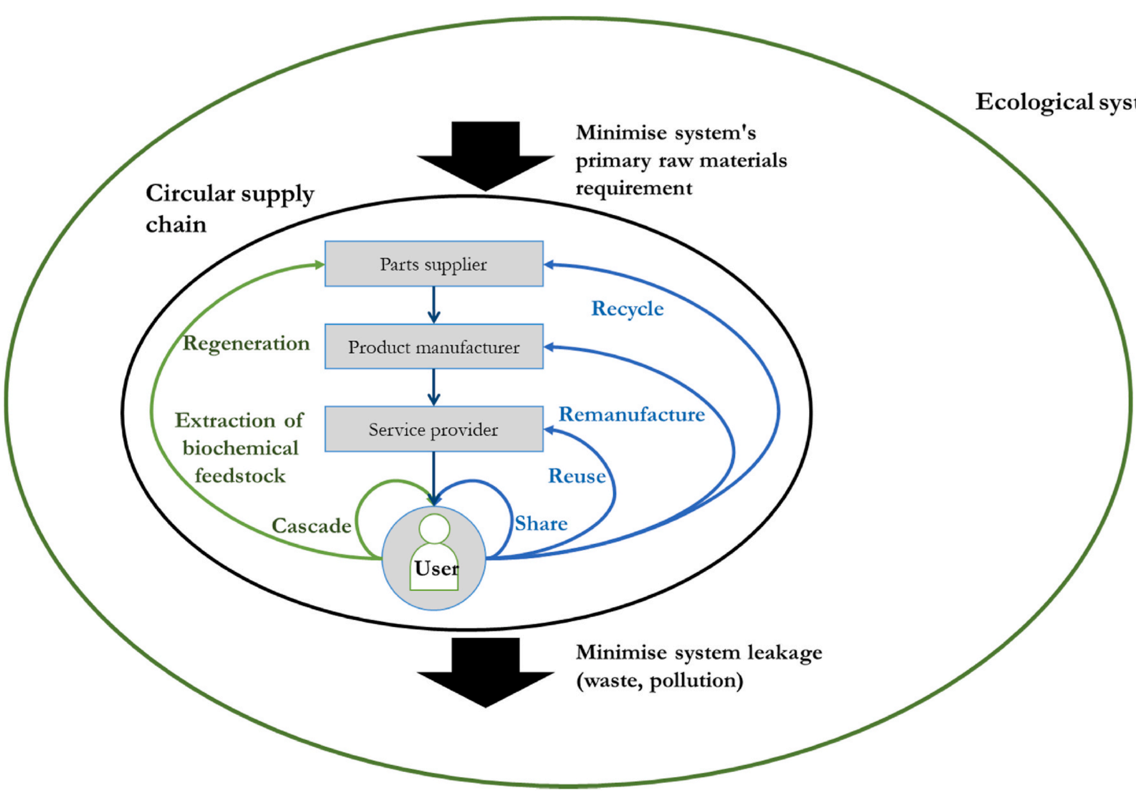

Fig. 1. Circular Supply Chain as part of the Ecological system (adapted from Bloemhof-Ruwaard, 2015).

respecting their natural reproduction rates (Korhonen et al., 2018a, b).

The Literature is currently exploring enablers of CSCs. Digital technologies (Acerbi and Taisch, 2020; Chiappetta Jabbour et al., 2020; Acerbi et al., 2021) the integration with supply chain partners (Herczeg et al., 2018; Bressanelli et al., 2019; Elia et al., 2020; Calzolari et al., 2021), as well as collaboration with external partners (Cricelli et al., 2021) seem to play a key role in supporting organisations to adopt CE practices.

2.1. Measuring sustainability in circular supply chains

Decision-makers need tools to evaluate the adoption of CE practices, and operationalise profitable, efficient, circular and sustainable supply chains. Decision support tools employ many CE indicators in order to account for a variety of impacts across boundaries between firms (Maestrini et al., 2017), concerning every dimension of sustainability (i.e. economic, environmental and social) (Fig. 2). CE indicators are formed by single or multiple metrics, which can be defined as the "finest level of granularity for assessment means" (Vinante et al., 2021).

CE assessment metrics, indicators and methods at the firm level have been extensively reviewed (Elia et al., 2017; Saidani et al., 2019; Sassanelli et al., 2019; Vinante et al., 2021). However, mentioned studies confirm that there is a lack of agreement on what needs to be measured, on standard methods of measurement and even on shared terminology and conceptualisation of the CE.

In SCM literature, some distinct research streams have developed tools to measure the adoption of CE practices with a supply chain level of analysis. The GSCM and SSCM literature (Brandenburg et al., 2014) is considered to offer insights about a crucial unit of action for implementing CE (Liu et al., 2018). Existing decision support tools (DSTs) incorporate a triple bottom line (TBL) approach and life-cycle perspective in the evaluation of impacts for complex and global supply chains (Acquaye et al., 2017; Genovese et al., 2017a). Indeed, in the GSCM and SSCM literature, the evaluation of environmental impacts makes extensive use of established methods found in environmental science (e.g. *LCA, Life-Cycle Costing*). Some variants of these methods (e.g. *hybrid LCA, Multi Regional I/O Frameworks*) are also able to rigorously assess the environmental performance of complex and global supply chains (Acquaye et al., 2017; Genovese et al., 2017a). Thanks to these methods, it is possible to determine supply chain *hotspots* (in terms of environmental impacts) using relevant key performance indicators (KPIs), thus identifying areas to be prioritised for action.

At the micro level of a single organisation, CE interventions support the design of reverse supply chains, recycling, reusing or remanufacturing end-of-life products. CLSCs should take back products from customers and return them to the original manufacturer for the recovery of added value by reusing the whole product or part of it (Rubio et al., 2008). RL and CLSCM research streams have firstly concentrated on the evaluation of the economic viability of CE practices, and have only recently moved towards integrated multi-dimensional impact assessments (Kazemi et al., 2019). No review of CE indicators with a supply chain perspective has been performed. The only very recent attempt is focused on methods and approaches, rather than on the considered indicators (Walker et al., 2021b).

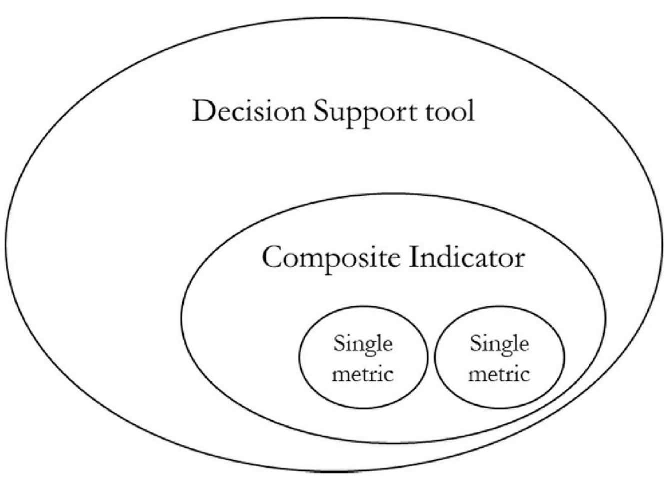

Fig. 2. Decision support tools, Indicators and metrics.

The literature on CE indicators for supply chains is very fragmented (Fig. 3). It is quite clear that a standard way to support decisions and keep track of the transition of supply chains to higher levels of circularity has not yet been defined. There is no clarity on what should be measured nor on the criteria that should be employed to select metrics, as well as objectives of DSTs. Many CE indicators, metrics or set of metrics have been used. Many DSTs employ economic metrics (e.g. costs, revenues, net present value) or environmental ones (emissions, energy, waste, resources consumed, resources recovered), and even social ones (jobs created by the CSC).

2.2. Understanding the choices behind DSTs for sustainability

DSTs for CSCs can be considered a subset of general sustainability tools (Gasparatos et al., 2008; Gasparatos, 2010; Gasparatos and Scolobig, 2012). When building DSTs, researchers and industrial practitioners have to choose how to systematically select among different metrics (Gasparatos and Scolobig, 2012) and whether to aggregate subsets of metrics into composite indicators. These choices are not just technical ones, but also constitute an important decision, in terms of value perception and worldview assumptions. Analysing general sustainability tools, Gasparatos and Scolobig (2012) identified three main approaches (Fig. 4), according to their underlying perspectives and conceptions of value:

- *Monetary tools* evaluate sustainability phenomena based on market-based evaluations. Environmental impacts are generally transformed into costs. These tools are linked to a *neoclassical* conception of value, which is related to a deeply anthropocentric view. Tools based on Cost-Benefit Analysis constitute a classical example of this category (Gasparatos and Scolobig, 2012).
- *Biophysical tools* focus on inflows and outflows of energy, materials and waste within a system. Usually, coefficients and algebraic rules are used to collapse the behaviour of a very complex system into a common unit of measurement, like in the case of EMergy accounting (Odum, 1996; Brown, 2018). This category also includes Life Cycle Assessment (LCA), which explores environmental impacts across products' production, usage and disposal stages. Such tools take an eco-centric approach to value– highlighting interconnections between economic activities and the environment (Daly and Farley, 2011).
- *Composite and Multi-Criteria approaches* usually bring together subsets of variables into multi-dimensional measures. A complex system's performance is subdivided into measurable pillars, where more sub-indicators capture different variables. These sub-indicators can be either aggregated into a single index, or presented as part of multi-criteria assessment frameworks. These tools are more flexible in terms of value considerations, which depend on specific weighting and normalisation assumptions (Martinez-alier et al., 1998).

No previous review has classified DSTs and associated indicators for CSCs by investigating their underlying assumptions, as per the framework introduced by Gasparatos (2012). In general, the current literature on DSTs for CSCs contributes to knowledge at a very practical stage, investigating specific decisions without questioning underlying world-views and assumptions (Korhonen et al., 2018; Kirchherr and van

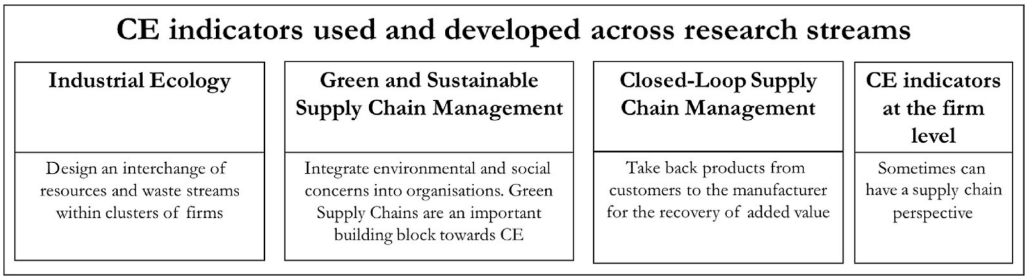

Fig. 3. Decision support tools and CE indicators in the CSCM literature.

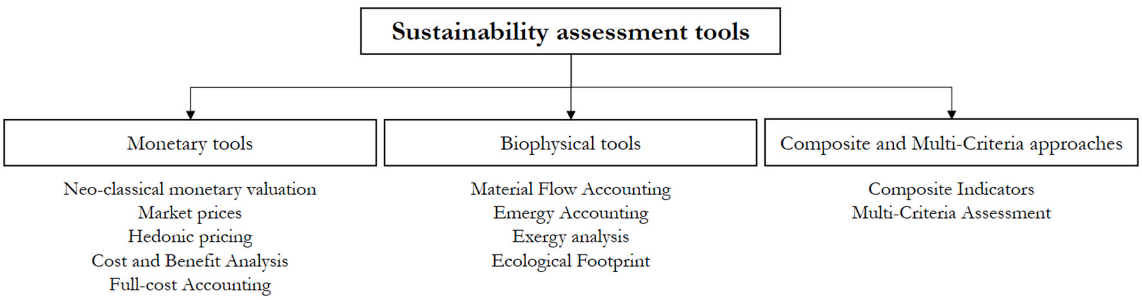

Fig. 4. Three classes of sustainability assessment tools (adapted from Gasparatos, 2012).

Santen, 2019).

2.3. Research gaps and research questions

The CE literature lacks an overview of the standard indicators and DSTs to evaluate the transition towards a CE in supply chains. Available CE assessment metrics, indicators, methods and methodologies in the academic literature have been reviewed at the firm level (Elia et al., 2017; Saidani et al., 2019; Sassanelli et al., 2019a; Vinante et al., 2021) and only recently at the supply chain level (Walker et al., 2021b). Existing CSC DSTs have employed different methods and used different criteria to select the metrics, and deal with trade-off decisions. On the basis of the identified gaps, the research questions that will be addressed in this study can be summarised as follows:

RQ1. What are the current CE indicators in the context of the CSC literature and in industrial practice?

RQ2. Can a subset of the most commonly employed metrics in both the academic literature and industrial practice be identified and compared?

3. Research method

In order to address the research questions, CE indicators were reviewed both in the academic literature and industrial practice, with two parallel analyses (Fig. 5, top part). A Systematic Literature Review was employed in order to identify the key scholarly contributions in the topic of CE indicators at a supply chain level. In parallel, a representative sample of organisations was reviewed to identify how industrial organisations keep track of the impact of the adoption of CE practices. The top-50 European Multi-National-Enterprises from the Global Fortune 500 list were identified as a representative sample. Results of these two analyses were then synthesised to identify subsets of commonly employed indicators, and also build two composite indicators that are then compared in the discussion section (Fig. 5, bottom part).

Academic literature and industrial reports have deeply different nature and scopes. DSTs in the literature support decisions on the adoption of new CE practices, adopting most often an *ex-ante* perspective. Corporate Sustainability reports tend to evaluate CE practices that have already been adopted by the company, taking an *ex-post* view. The comparison of the two bodies of knowledge will also allow checking the correspondence between adopted indicators across different contexts and perspectives.

3.1. Systematic review of the literature – CE indicators for supply chains

Through a scientific, replicable and transparent process the SLR method identifies the key contributions that are relevant to a particular research question (Denyer and Tranfield, 2009). In this case, the objective was to assess the state of the art of the measurement approaches that have already been developed for assessing the transition towards the CE at the supply chain level. As suggested by Maestrini et al. (2017), the review included four main phases (Maestrini et al., 2017): (i) source identification, (ii) source selection, (iii) source evaluation, and (iv) data analysis (Fig. 6). These four phases are illustrated in the following sub-sections.

3.1.1. Source identification

The source identification phase was conducted using the SCOPUS and Web of Science peer-reviewed academic databases. The use of two sources in parallel increased the rigour of the selection process (Denyer and Tranfield, 2009). Keywords were chosen to maximise the number of articles to be included in the analysis. Therefore, the IE, CLSCM and RL literature streams were included, as they have contributed to the origins of a CE discourse in the supply chain management literature (Batista et al., 2018; Sehnem et al., 2019). The following string of keywords was used:

(('Circular Economy' OR 'Circular' OR 'Closed-loop' OR 'Reverse' OR 'Industrial Ecology' OR 'Industrial Symbiosis') AND 'Supply Chain*' AND ('indicator*' OR 'measur*' OR 'assess*' OR 'index*' OR 'metric*'))

A manual cross-checking process was conducted in order to eliminate duplicated results. At least two of the research team members executed the overall process in parallel and independently, as suggested by Maestrini et al. (2017). Table 1 provides the results of the search protocols.

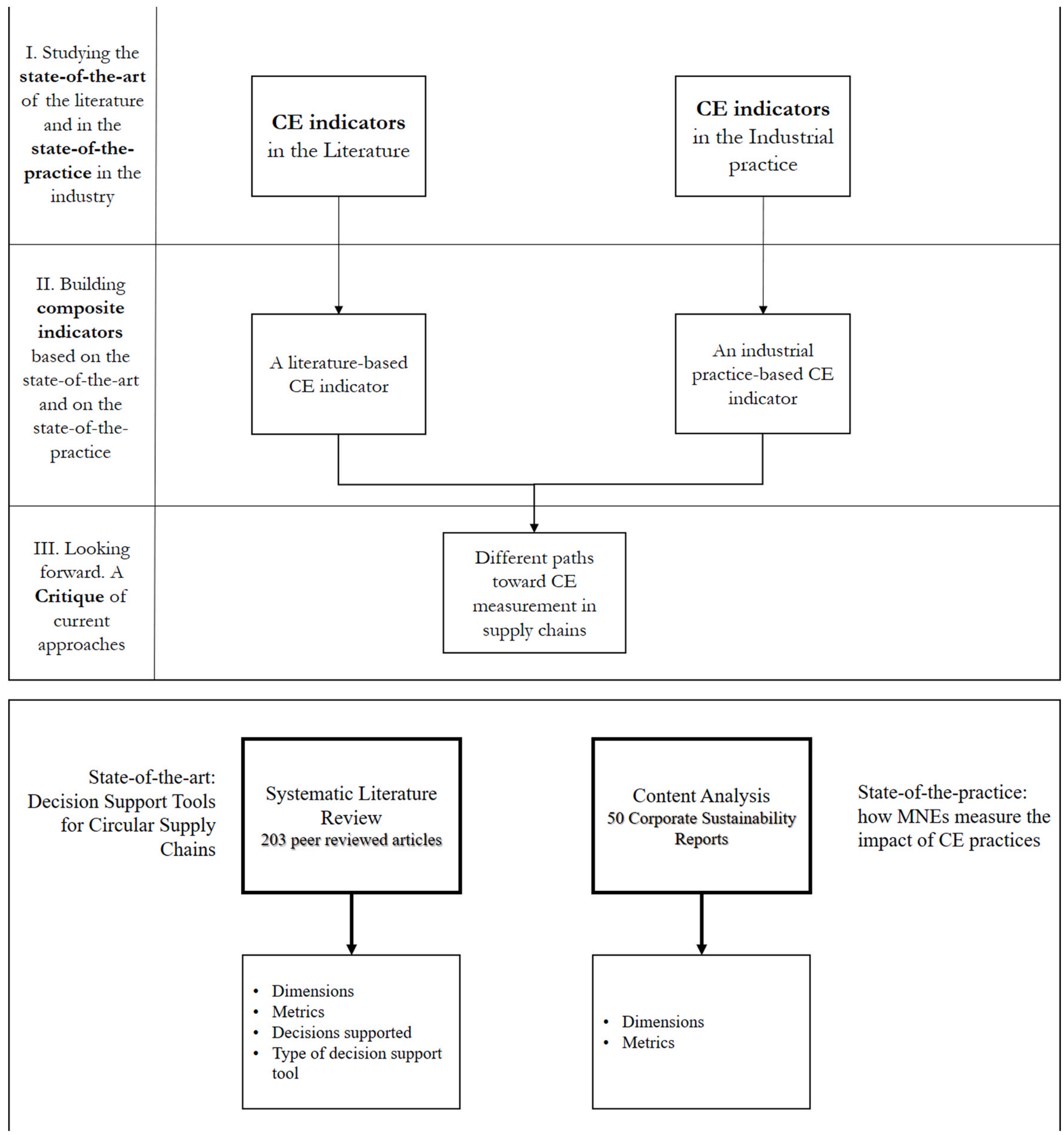

Fig. 5. Research methods diagram. Review of the literature and of the industrial practice protocol (top); approach followed for the derivation of literature and practice-based composite indicators (bottom).

3.1.2. *Source selection*

Once the subset of potentially relevant articles was identified, a first selection process was performed on the abstracts. To delineate the boundaries of the analysis the following inclusion/exclusion criteria were applied:

- Only articles in English language have been *included.*
- Only peer-reviewed papers were included; book chapters and conference papers have been *excluded.*
- Publications which did not develop or employ indicators or measurement systems have been *excluded.*
- Publications that considered the circular dimension of SCs (at least as a potential state) were *included.* If the focus was only on the forward element of a supply chain, articles were *excluded.*
- Studies were classified on the basis of the specific implementation levels that can be recognised in the CE literature (Ghisellini et al., 2016; Korhonen et al., 2018a,b): the micro level, involving CE strategies at the product and firm level, thus involving an intra-organisational decision-making process; the meso level, including supply chains and, in some contexts, also related to Eco-Industrial Parks and Industrial Symbiosis systems (Masi et al., 2017); the macro level, including CE development in regions and nations (Ghisellini et al., 2016; Kirchherr et al., 2017). Based on this classification:

o Papers defining indicators to assess CE at the macro level were *excluded* from the analysis.
o Papers developing indicators and measurement approaches at the meso level were *included* in this SLR. Papers that did not consider the SCs as the level of analysis have been *excluded.*
o Papers defining specific indicators to measure CE initiatives at the micro perspective of the single organisation, were evaluated in detail. A decision was made on the basis of the explicit

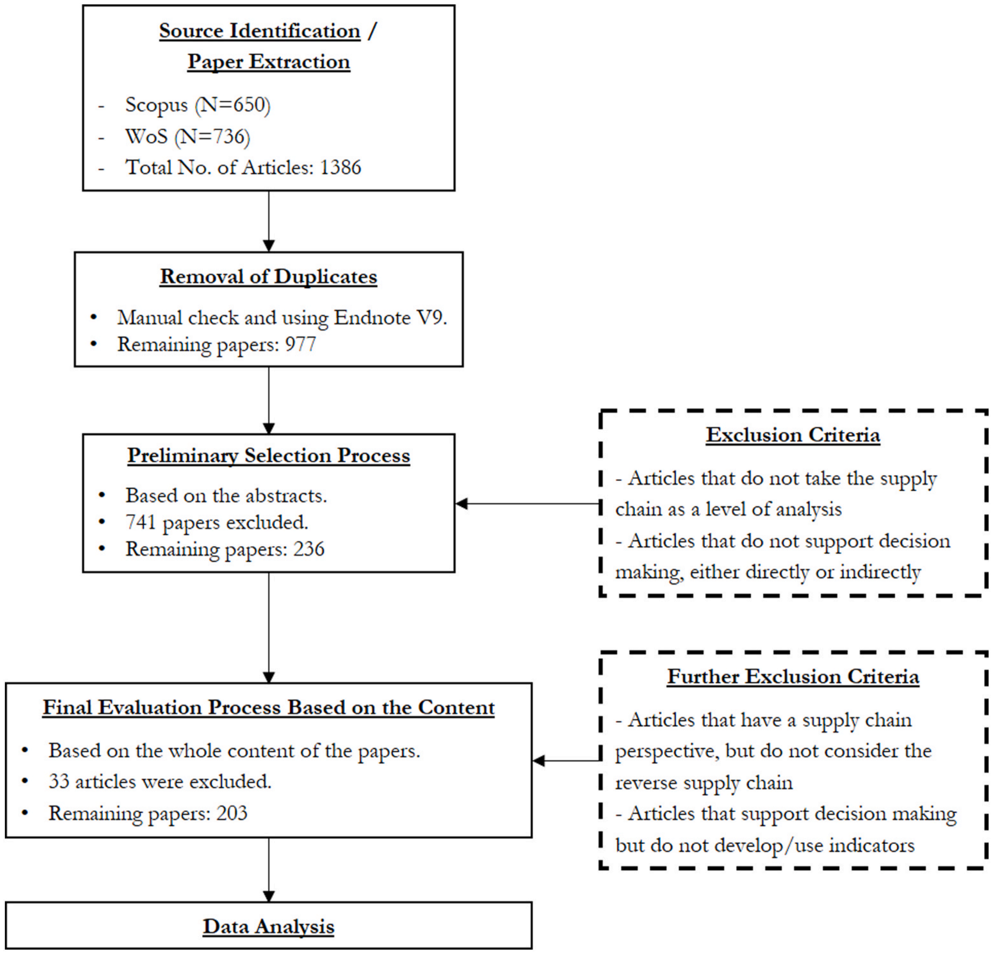

Fig. 6. Papers search and evaluation process.

Table 1
Articles searching protocols.

Database	Fields of search	Language	Subject Area	Document Types	Total	Total Both	Duplicate	Remaining
Scopus **WOS**	Article title, Abstract, Keywords Topic	English	No restrictions	Article; Review	650 736	1386	409	977

consideration given to the role played by supply chains (EMAF, 2015; De Angelis et al., 2018). Just studies assuming an inter-organisational perspective for the employed indicators were *included.*

This scanning process resulted in a large reduction in the number of papers (from 977 to 236). Also this phase was handled separately and autonomously by at least two members of the research team. Regular team meetings were held throughout this phase and the following ones, in order to compare the choices adopted and to ensure that the process was rigorous. Inter-reliability was satisfied by considering the number of disagreements over the number of papers classified; all the disagreements were examined one by one to come to a collective consensus. Articles that could not easily be excluded with the highest degree of certainty, were included to be further analysed and read in the source evaluation phase.

Table 2
Criteria for selecting articles.

Criteria	Number of Studies	Relevance
Studies developing an indicator/multiple indicators in order to explicitly evaluate the performance of CSCs	63	*Included*
Studies employing an indicator/multiple indicators for CSCs in the context of wider Decision-Making models	140	*Included*
Studies contributing to the CE literature without developing any indicator	33	*Excluded*

3.1.3. Source evaluation

The resulting 236 articles were evaluated and classified from a relevance point of view in relation to the criteria described in Table 2. In particular:

- Studies developing an indicator/multiple indicators in order to explicitly evaluate the performance of CSCs were *included.*
- Studies employing an indicator/multiple indicators for CSCs in the context of wider Decision-Making models and problems were *included.*
- Studies contributing to the CE literature without developing any indicator were *excluded.*

Table 3
Indicators classification dimensions.

Classification Dimension	Example
Authors	Taskhiri, M.S.; Jeswani, H.; Geldermann, J.; Azapagic, A.
Title	Optimising cascaded utilisation of wood resources considering economic and environmental aspects
Year	2019
Source	Computers & Chemical Engineering
Decision type	Strategic
Detailed Decision	Circular Supply Chain Network Design - Comparing alternative scenarios
Modelling approach	Mathematical programming method
Research Method	Optimisation (& Life Cycle Assessment)
Detailed Research Method	Mixed Integers Linear Programming
TBL Dimensions considered	Economic & Environmental
Economic metrics	Circular Supply Chain Cost
Environmental metrics	Global Warming Potential (GWP); abiotic depletion potential of resources (ADP); acidification potential (AP); eutrophication potential (EP); freshwater aquatic ecotoxicity potential (FAETP); human toxicity potential (HTP); marine aquatic ecotoxicity potential (MAETP); ozone depletion potential (ODP); photochemical ozone creation potential (POCP); terrestrial ecotoxicity potential (TETP)
Social metrics	–
Single/Multiple/ Composite indicator	Multiple indicators
Weighting Method	Development of a Pareto-efficient frontier – indicators are kept separate
Class of Sustainability DST	Indicators, Multi-Criteria

Another 33 articles were excluded, because they did not develop or use any indicator; thus, 203 articles were shortlisted for the purpose of the analysis. Also for this process, at least two team members operated independently, assigning each paper to each category according to the four criteria as suggested by Maestrini et al. (2017).

3.1.4. Data analysis

Finally, a critical analysis of the 203 shortlisted articles was performed, with the aim of summarising the relevant findings and highlighting the messages. Existing models were surveyed, on the basis of the research method employed, the types of decision supported, the sustainability dimension considered and the indicators employed. Single metrics were tracked, in order to understand the most popular ones. DSTs that employed multiple metrics were also classified according to normalisation and/or aggregation approaches. An overview of the classification dimensions is provided in Table 3.

3.2. Review of CE indicators in the industrial practice

This part of the study identifies the homogenous metrics that are reported by companies when they evaluate the adoption of CE practices. The amount of data that organisations make public has been enhanced because of the greater accountability and transparency demanded to MNEs (Hahn and Kühnen, 2013) by a set of stakeholders (e.g. employees, customers, suppliers, pressure groups, investors, regulators). Also the quality of data, regarding their economic social, and environmental impacts and actions, has been enhanced and follows increasingly standardised guidelines (e.g. Global Reporting Initiative[1]). Corporate Sustainability reports represent an ideal platform for evaluating the adoption of CE practices and for identifying KPIs in industry. These reports can be seen as the most direct statement concerning sustainability practices (and, more specifically, CE practices) adopted by a firm (Stewart and Niero, 2018).

This review consisted of four main phases: (i) sample definition, (ii) content extraction, (iii) data coding and (iv) data analysis (see Fig. 7). The Global Fortune 500 list[2] (2019 edition) was used to select the sample – which includes the Top-50 companies in the list from the European Economic Area[3] (EEA). A template analysis technique (King and Brooks, 2018) was used to analyse the content of the reports in order to identify KPIs related to sustainability and CE practices. During the data extraction phase, reports were read in their entirety. The body of text of interest for the research questions was identified, extracted, collected through the NVivo software package, and then organised using an Excel spreadsheet. A keyword-based final check made sure that all the relevant text had been captured from all the reports. Keywords were related to the type of impact category (e.g. emissions, waste, and energy). Such a procedure was aimed at achieving the maximum level of replicability of the analysis.

4. Results

In this section, the main results from the analysis of the article sample are reported. The first part focus on the SLR. The following subsection discusses indicators from the industry and the final sub-section proposes two CE indicators.

The sample analysed includes 203 papers from 99 different sources. Journals belong to different research areas, as CE topic has an interdisciplinary nature. Three out of the four most represented journals belong to the Environmental Science literature (Table 4). An emerging interest comes from Industrial Engineering literature (e.g. International Journal of Production Economics; International Journal of Production Research) and from Decision Science and Operational Research disciplines. Publications range from 2002 to 2019; there has been a sustained growth in the number of papers published starting from 2015 (Fig. 8).

Most of the publications support decisions at a strategic level (Fig. 9), and more precisely related to the *design of CSCs*. Design decisions include locating and sizing facilities (e.g. industrial plants, distribution centres, collection centres, recycling centres disposal centres), selecting technologies and transportation modes. Some publications support tactical decisions, linked with the *planning of CSCs.* This means deciding how to size the production lots, manage inventory, and coordinate with other supply chain partners. Some papers include elements of both strategic and tactical planning. A significant group of articles does not support directly any specific decision (Unspecified), rather aiming at *measuring the performance of CSC Networks*. These papers develop and use indicators to map and evaluate specific CSC processes, or to compare alternatives CSC configurations. Their focus is more on the ex-post measurement rather than on supporting specific decisions directly. For this reason, they were distinguished from tools directly supporting design and planning decisions.

The majority of the publications employ methods from the Operational Research tradition, namely Mathematical Programming and Simulation (Fig. 10). Optimisation models (such as Mixed Integer Linear Programming) can employ either single or multi-objective functions decision variables. Some articles employ analytical models; these tools are either Multi Criteria Decision Making (MCDM) method based or Environmental Science approaches. Among these, LCA is the most common, followed by Input/Output and Material Flow Analysis models. Other tools employ a mix of these methods (like LCA and Ecological Network Analysis) or cost-based models (Material Flow Cost Analysis or Life Cycle Costing). The distribution in terms of modelling approaches represents the main difference with previous reviews on CE indicators at the firm level (Sassanelli et al., 2019a; Vinante et al., 2021). These reviews have not included CLSCM and RL research streams, which make a

[1] https://www.globalreporting.org/.

[2] https://fortune.com/global500/.

[3] EEA includes EU countries and also Iceland, Liechtenstein, and Norway. The list of companies was compiled on the 1st of January 2019; it reflects, then, EU membership at that date.

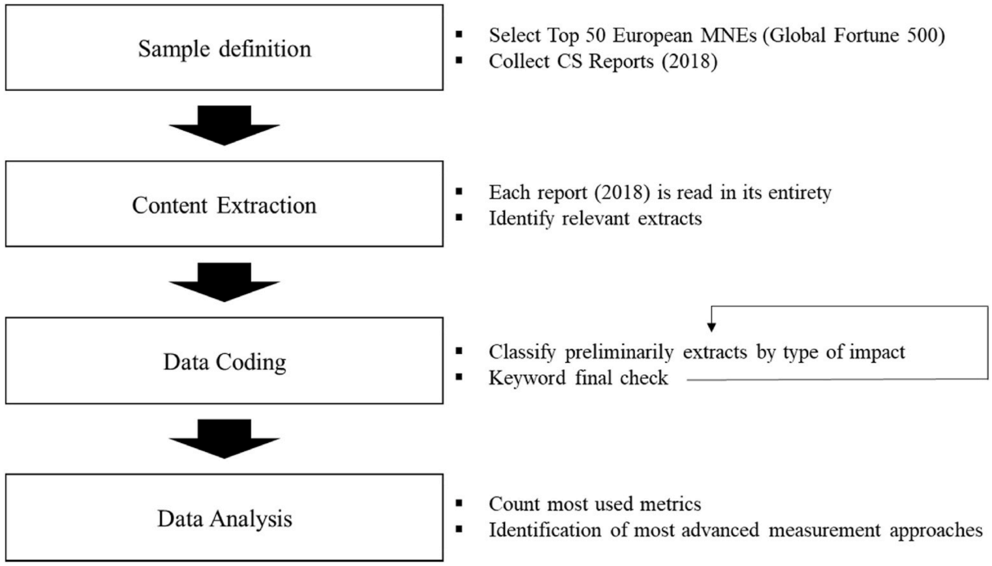

Fig. 7. Content Analysis flowchart. CS reports: Corporate Sustainability Reports.

Table 4
Top 10 Journals that exhibit the highest number of papers.

Source	Number of publications
Journal of Cleaner Production	25
International Journal of Production Economics	16
Sustainability (Switzerland)	10
Resources, Conservation and Recycling	9
International Journal of Production Research	8
Computers and Industrial Engineering	7
Applied Mathematical Modelling	6
Science of the Total Environment	4
European Journal of Operational Research	4

frequent use of Operational Research methods. However, this figure is aligned with the only review that focus on sustainability assessment at the supply chain level (Walker et al., 2021b).

4.1. Metrics and dimensions

In line with RQ1, the articles reviewed were classified according to the sustainability dimensions they consider and the single metrics they select. The TBL approach is a central concept in sustainability studies, where performance standards need to be achieved across environmental, economic and social dimensions. Following the inclusion of environmental and social issues in the public agenda, SCM scholars have gradually incorporated adequate indicators in their models (Seuring and Müller, 2008).

Only 15% of the 203 papers integrate the three dimensions simultaneously (Fig. 11). The great majority of the papers (82%) do not consider social indicators, favouring the economic and the environmental dimensions. An interesting result is that 34% of the papers do not consider, in an explicit manner, environmental issues; many of these studies incorporate reverse logistics considerations, which (as explained in Section 2.1), were at first mainly based on economic aspects. This result highlights some differences in the choices between firm and supply chain level DSTs. Firm level DSTs seem to incorporate more often environmental considerations (Sassanelli et al., 2019a).

Half of the articles in the sample adopt a single-dimension perspective, mainly favouring the economic (32%) and the environmental (18%) dimensions. Nevertheless, looking at how the consideration of sustainability dimensions has evolved over time, it can be seen that an increasing number of studies account for at least two dimensions (Fig. 12). Individual dimensions and employed indicators are discussed in detail in the following subsections (Table 5).

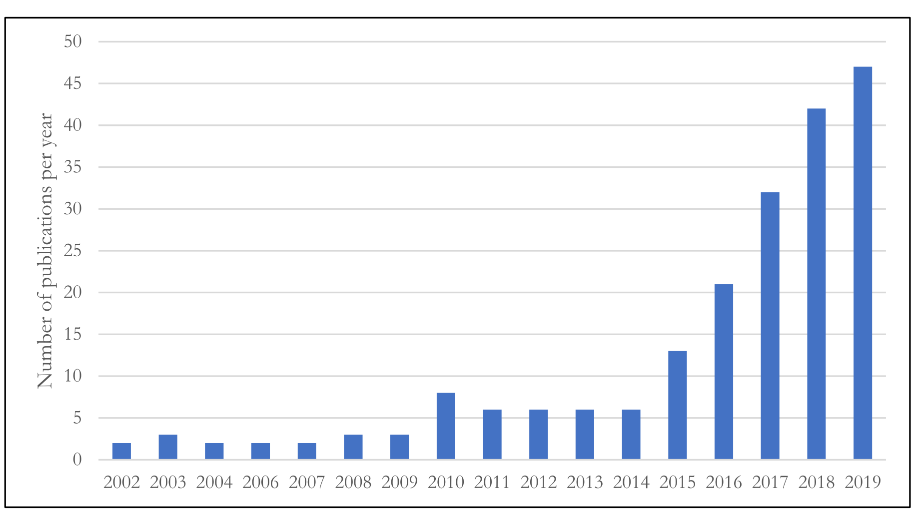

Fig. 8. Historical series of published papers.

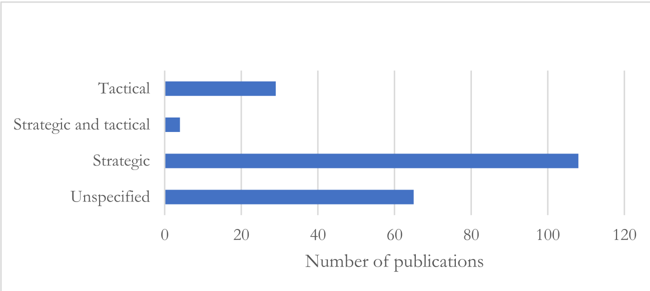

Fig. 9. Type of decision supported.

4.1.1. Economic indicators

80% of the studies employ economic indicators, with a clear prevalence of cost-based measures (Table 5). Notable examples include cost of production, transportation cost, facility location cost (Özceylan and Paksoy, 2013; Shankar et al., 2018; Ponte et al., 2020). These considerations are very common in CSC Network Design Optimisation models. Indicators related to the time responsiveness of the CSC and to the quality of the products are less common (Kazancoglu et al., 2018; Liao et al., 2020). Some CE indicators can be noticed across the different categories of measures. Notable examples are the cost associated with reverse supply chain activities, the profits associated with recovery activities (Baptista et al., 2019; Jin et al., 2019), including remanufacturing (Abdi et al., 2019), recycling (Li et al., 2019), and the quality of the recovered products after the end of their life (Jeihoonian et al., 2017).

4.1.2. Environmental indicators

Most of the studies that consider the environmental dimension utilise indicators based on Global Warming Potential and Greenhouse Gas Emissions (Tsoulfas et al., 2002; Low et al., 2016; Chavez and Sharma, 2018; Rezaei et al., 2019; Taleizadeh et al., 2019). Emission equivalent (such as CO_2-eq) metrics are three times more likely to be employed than any other category of environmental indicators, which seems to confirm that SCM literature has an established carbon-centric point of view (Genovese et al., 2017b).

Fewer studies select indicators related to the residual waste that is incinerated or landfilled (17%), or on waste recovered thanks to CSC feedback loops (Rachaniotis et al., 2010; Jayant et al., 2014; Gusmerotti et al., 2019). Other commonly utilised indicators focus on use of energy across supply chains (Genovese et al., 2017a). Cumulative energy demand (CED) considers the energy consumed throughout the product lifecycle, including the extraction of raw materials, manufacturing, distribution and disposal phases (Govindan et al., 2016; Sgarbossa and Russo, 2017; B. Liu et al., 2018). Only 13% of the articles measure the quantity of virgin resources (e.g. minerals, fossil fuels, renewable resources) that are depleted throughout the supply chain (Rao, 2014; Daaboul et al., 2016; Hazen et al., 2017).

In total, 77 different environmental indicators are employed. This denotes the lack of an agreed standard for measuring the environmental performance of CSCs, or the transition of supply chains towards CSC configurations. Many studies use traditional LCA frameworks, in this way taking into account a wide variety of impacts across the whole product supply chain.

Another relevant gap is the absence of explicit metrics regarding process or material ‘circularity’. Only a very small minority of papers employ specific indicators to measure the proportion of waste and by-products reincorporated in the supply chain (Wei et al., 2014; Gilbert et al., 2017; Jeihoonian et al., 2017; Al-Aomar and Alshraideh, 2019).

4.1.3. Social indicators

Only 18% of the sample consider the social dimension within the definition of the objectives (Darbari et al., 2019; Taleizadeh et al., 2019). It can be observed that there is no agreement on the stakeholders to be involved. Some measurement approaches only consider employees, whilst others consider customers and as well as suppliers, organisations or communities (see Table 5).

The most common indicator (which appears in 7% of the papers included in the sample) is represented by the employment opportunities generated within the supply chain (i.e. the total number of jobs created by the CSC). Whilst not common, some metrics representing the ‘quality’ of the jobs created are also considered: 3% of these indicators mention aspects such as the presence of decent work conditions (Rahimi and

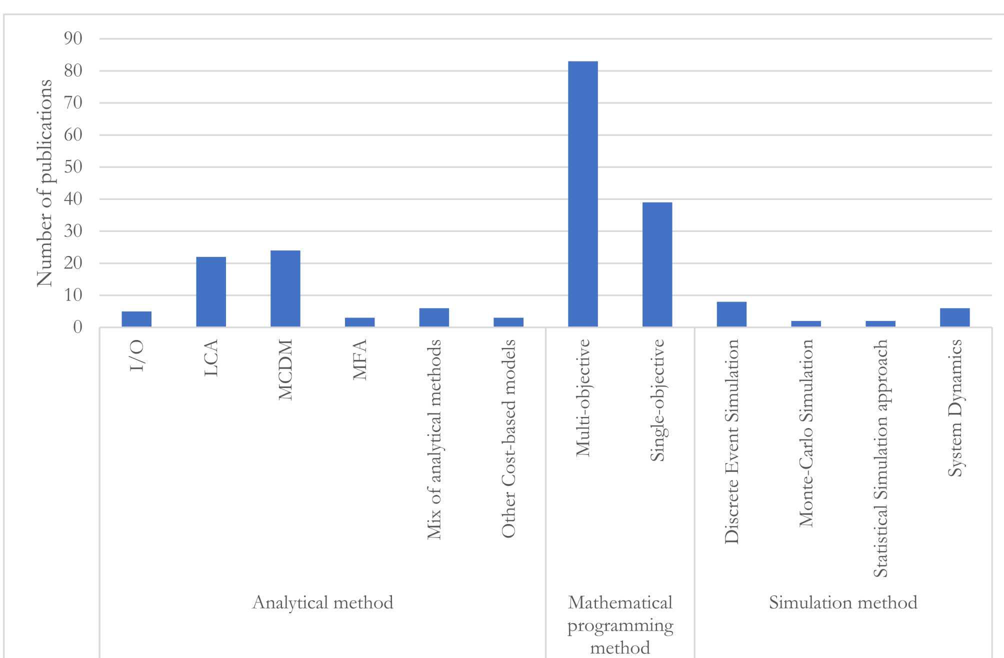

Fig. 10. Modelling approaches following the classification from Brandenburg et al. (2014). ENA: Ecological Network Analysis; I/O: input/output models; LCA: Life Cycle Assessment; MCDM: Multi-Criteria Decision Making models; MFA: Material Flow Analysis.

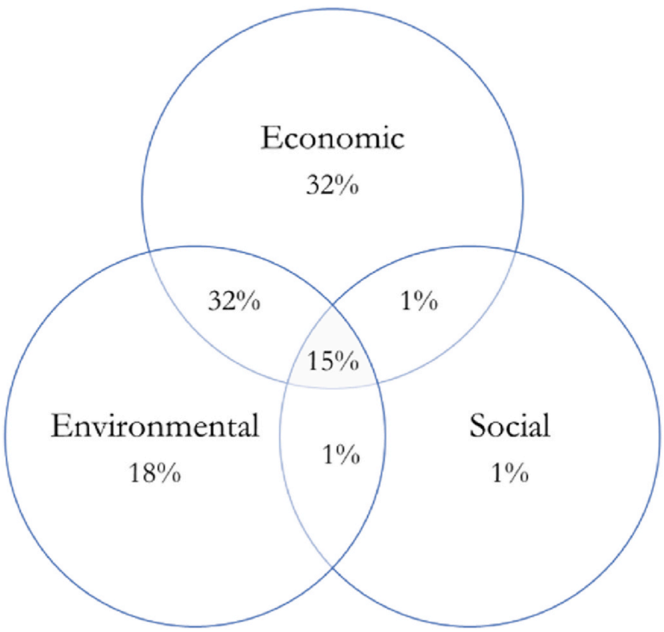

Fig. 11. Dimensions considered by the existing models and tools in the literature.

Ghezavati, 2018; Hajiaghaei-Keshteli and Fathollahi Fard, 2019), 2% of employee training opportunities (Govindan et al., 2016) and other benefits for workers.

A less common indicator (which appears in just 1% of the papers considered) measures customers' environmental awareness, related to their willingness to return used products at the end of their life (Govindan et al., 2016; Gusmerotti et al., 2019). Another notable indicator describes the social cost of waste (1%), defined as a penalty cost assigned to companies for disposal of materials throughout the supply chain.

4.1.4. A classification of existing measurement approaches

In this section articles are classified by looking at the work of Gasparatos and Scolobig (2012) on general sustainability assessment tools, characterising existing measurement approaches on the basis of the underlying conceptual assumptions. Three DST classes could be identified (Table 6). Each class of tools shows a good degree of similarity in terms of DST objective, research method adopted, sustainability dimension considered, and metrics selected. Each class also reflects very similar assumptions of value. The three classes of CSC DSTs can be defined as follows:

1. *CSC Monetary tools (88 papers)* support decisions by looking mainly at the economic viability of CSCs. As a consequence, within these tools the economic dimension is prevalent. 63 out of 88 DSTs do not consider at all environmental and social metrics. The other 25 consider multiple dimensions and convert environmental and social impacts in monetary terms to become part of a general cost function. Usually, they employ simplified environmental indicators, mainly based on carbon emissions which are translated into measures of carbon emission costs. Only 4 out of 88 tools select indicators related to the circularity of material flows or to waste creation at the different stages of the supply chain. 79 out of 88 use mathematical programming or simulation approaches. This class encompasses articles that have an acceptance of *neoclassical* value assumptions.
2. *CSC Biophysical tools (29 papers)*: This class collects mainly tools based on environmental and systems sciences approaches. Articles have the objective of quantifying flows and stocks of materials within supply chains and calculating environmental impacts associated with those flows. The methods employed are mainly LCA, Material Flow Analysis (MFA), hybrid LCA, and environmental I/O methods. The type of decision supported is mainly at the strategic level (e.g. comparing different products, processes and CSCs); chosen metrics are purely environmental. They are usually not aggregated or normalised into composite indicators. The type of value consideration of these tools is *eco-centric*: production and consumption systems are evaluated on how much resources they are consuming, how much waste they produce and how much and how they affect natural systems.
3. *CSC Composite and multi-criteria indicators (86 papers)*: these tools consider multiple dimensions at the same time; just 9 over 86 focus on just one dimension. Their objective is to combine performances offered by alternative solutions across different criteria, assisting decision-makers in selecting the best course of action according to their preferences. MCDM and multi-objective mathematical programming approaches are the most commonly employed methods. Within these approaches, a first group of papers (38) normalise and combine all the different aspects into a single index. These DSTs

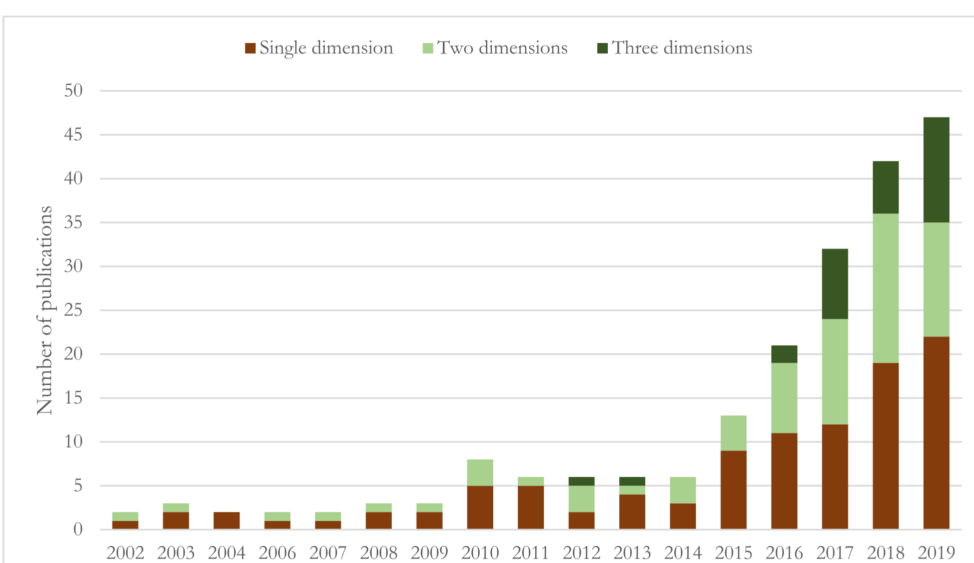

Fig. 12. Interactions between the different methods considering sustainability dimensions and scale of interest.

Table 5
The most commonly employed metrics.

TBL Dimension	Category	Metrics	Description	Occurrences	%
Economic	Costs	• Operational costs • Facility location costs • Transportation cost • Reverse supply chain cost	Cost-based indicators, both at a company and at a supply chain level	112	55%
	Profits	• Total CSC profits • Profits from recovery activities including remanufacturing, recycling and disposal	Profit-based indicators, both at a company and at a supply chain level	50	25%
	Time	• Time responsiveness of the network • Delivery reliability of suppliers	Time responsiveness-based indicators, both at a company and at a supply chain level	18	9%
	Quality	• Reliability of supply • Quality level of the production • Quality of the returns	Quality-based indicators, both at a company and at a supply chain level	14	7%
	Risk	• Financial risk • Value at risk • Conditional value at risk • Variability index • Downside risk	Risk-based indicators associated to uncertainty (e.g. of demand, collection)	12	6%
	Profitability	• Net Present Value • Return on Equity • Return on Assets	Profitability-based indexes, measuring	9	4%
Environmental	Emission equivalent	• Climate Change • Greenhouse gases • Global Warming Potential	CO2 eq. emissions associated with supply chain	90	44%
	Waste	• Waste Landfilled • Recycled waste • Recovered waste • Recyclability and ease of disassembly	Residual waste produced and landfilled or recovered by supply chain activities	35	17%
	Energy usage	• Energy use • Cumulative energy demand • Renewable energy use • Energy self-sufficiency	Energy-based indicators associated with supply chain	32	16%
	Virgin resources usage	• Abiotic depletion of resource • Mineral, fossil & renewable resource depletion	Virgin resource use associated with supply chain material consumption	26	13%
	Water	• Water depletion • Water emissions • Water use	Water used or contaminated	26	13%
	Air emissions	• Particulate Matter • Respiratory inorganics	Other air emissions associated with supply chain	22	11%
	Acidification	• Terrestrial acidification • Marine acidification	Acidification potential associated with supply chain processes	19	9%
Social	CSC jobs created	• Number of fixed and variable jobs • Number of drivers hired for transportation	Employment opportunities provided by the CSC	15	7%
	Organisational H&S compliance	• Compliance with the ILO guidelines	Measures of compliance to H&S Guidelines for the jobs created in the CSC	7	4%
	Quality of work	• Work damages • number of accidents, lost • Employee turnover	Measures of quality of the jobs created	7	3%
	Training	• Average hours of training • Training on skills for employability	Indicators of the training provided to workers	4	2%
	Expenditure on Benefits for employees	• Food • Transportation • Pension	Indicators of benefits provided to the workers	4	2%
	Customer environmental awareness	• Enlightening customers to return end of used product • Customer incentives for recovery from discarded product	Indicators of environmental awareness of the customers	3	1%
	Social cost of waste	• Penalties and costs for disposal	Social cost of waste produced. Sum of disposal cost and of the cost for the recycler	2	1%

weight and aggregate more metrics into a *composite indicator*. A second group of studies (48) do not perform normalisation and weighting operations, rather keeping separate aspects that might not be comparable, doing sensitivity analysis and showing alternative solutions (*multi-criteria* methods). Decision-makers are left with a qualitative evaluation of the different profiles of dominant, non-dominated and dominated solution. Also *multi-criteria tools* consider simplified environmental indicators and often normalise different metrics into an synthetic index, which can be considered a proxy of all the environmental impact dimensions. Value considerations within these models are complex given the multiple dimensions involved.

4.2. CE indicators from industry practitioners

Also this section contributes to addressing RQ 1, highlighting CE indicators being employed in industrial practice.[4] Indicators of the economic impact of CE practices adoption vary according to the industrial sector and to the type of practice. 'Revenues from remanufactured products' is a common indicator among the manufacturing companies

[4] The following results refer to the analysis of the Corporate Sustainability reports of the Top-50 companies from the European Economic Area (EEA), according to the Global Fortune 500 list (2019 edition).

Table 6
Objectives, methodological approaches, and metrics of different classes of articles in the literature.

Type of tools	Objective	Methodological approach	Economic metrics	Environmental metrics	Social metrics	Aggregation Technique	Value	Examples
CSC Monetary tools	Evaluate the economic viability of CSCs	Mathematical programming; Simulation	Cost-based	Emission based	CSC jobs created	choose an efficient solution on the Pareto frontier	Neoclassical economics Utility-based; anthropocentric	(Baptista et al., 2019; Polo et al., 2019)
CSC Biophysical tools	Evaluate CSCs impact on Nature	LCA; MFA; I/O Analysis; Hybrid I/O LCA	No	mainly standard LCA based metrics/ material, waste flows	No	do not aggregate; aggregate per type of impact (Recipe, Eco-indicator 99)	Eco-centric	(Prosman and Sacchi, 2016; Hoehn et al., 2019)
CSC Composite and Multi-Criteria indicators	Combine multiple performances	MCDM; Mathematical programming	Cost-based	Emission based	CSC jobs created	normalise all the metrics into one composite indicators; identify many dominant and dominated solutions on an efficient Pareto frontier	Flexible	(Chavez and Sharma, 2018; Darbari et al., 2019)

that built an infrastructure to recover end-of-life parts to be sold in the secondary markets (*Renault, FCA, PSA, Volkswagen, Daimler, and BMW*). In the financial sector, economic indicators refer mostly to the 'green' investments associated with CE activities or with the promotion of renewable energy or resource efficiency solutions.

Most of the adopted environmental KPIs are *efficiency* indicators (Table 7), which compare a measure of polluting activities (for instance, carbon emissions) to the total production output. It must be highlighted that the usage of such indicators for measuring the success of CE practices is problematic. Figures could be manipulated to obtain better results, for example just by increasing production volumes (for instance, through productivity improvements), rather than by implementing practices which can promote a more parsimonious usage of resources. Social impacts associated with CE practices are assessed only by 4 organisations and refer to employment opportunities provided by the CSC.

Just one company, the Italian Energy Utility provider *Enel*, develops a measurement system to assess the level of circularity of its solutions and products. Enel *X Circular Economy Score*[5] evaluates five CE key dimensions (commitment by suppliers to CE principles; the presence of reusable elements which can increase the life-cycle of the product; the resource efficiency; the reuse of materials; and the support offered to suppliers) and circular business models (inter alia: product as a service; sharing platforms; product life cycle extension).

4.3. Developing CE indicators for supply chains from the state-of-the-art

This final section addresses RQ 2. The results of the reviews of the academic and of industrial practitioners' literature are used to identify appropriate subsets of KPIs from the three dimensions of sustainability (i.e. economic, environment and social). KPIs are then aggregated into two distinct CE composite indicators. These two prototypes could form the basis of DSTs that could be used to keep track of the effectiveness of CE interventions in CSCs; to focus on the trade-offs between different sustainability dimensions; and to account for benefits, impacts and preferences of different decision-makers and stakeholders.

4.3.1. A literature-based CE composite indicator for supply chain

The first multi-objective composite indicator is based on the results of the systematic literature review. This Literature-based CE index (L-CEI) aims at synthesising the models and tools already developed in the literature. The steps for the definition of this indicator are presented below:

- The weights of the three components representing the sustainability dimensions have been determined on the basis of their relative frequencies (as reported in Table 8). For instance, the weight of the economic dimension is 0.49 as this represents the normalised frequency of articles accounting for economic factors (with respect to a normalisation factor that is the sum of the percentage of articles reporting of each dimension).
- The subset of indicators considered for each dimension has been determined by considering the most popular metrics in the subset of papers selected in the review. The three most popular metrics have been selected for each dimension. Weights have been determined in a similar manner to what has been done for dimensions, considering normalised relative frequencies (Table 9).

Fig. 13 shows the hierarchical framework of L-CEI, its components and the respective weights. The economic dimension dominates, and accounts for around half of the total weight. The metrics are mainly cost-based and profit-based measures. A small portion (0.05) is attributed to a parameter representing the Time Responsiveness, which measures the time taken by the supply chain to move materials and components in the forward and the reverse supply chain.

Among the environmental metrics prominence is given to the CO_2-eq. emissions parameter. The 'Energy use' and 'Virgin Resource use' metrics have a similar and limited importance (0.08 and 0.07), and account for how intensively the supply chain makes use of energy and of primary resources. The Social component just accounts for 11% of the weight; within this dimension, selected metrics include the employment opportunities of the reverse supply chain 'CSC Jobs created' (0.05), and some measures of the quality of jobs, such as compliance to Health & Safety standards and 'Quality of work'. This last measure usually includes the number of accidents that cause workers' injuries across supply chain activities.

4.3.2. An industry-based CE composite indicator for supply chain

The second prototype, the Industry-based CE index (I-CEI), is based on the results of the previously presented review of the industrial practice (Section 4.2). The steps for the definition of this indicator are presented below:

- The weights of the three components representing the sustainability dimensions have been determined on the basis of the relative frequencies, in analogy with the calculations shown for L-CEI.
- The subset of indicators considered for each dimension has been determined by considering the most popular metrics in the sample. The three most popular metrics have been selected for each dimension. The relative weights inside each dimension have been chosen

[5] Enel X Circular Economy Score.

Table 7
Commonly used economic, environmental and social KPIs for European MNEs.

Dimension	Category	Examples	Description	Adopting Companies
Economic	Revenues	• Revenues from remanufactured products • Revenues from 'green products'	Revenues associated with CSC activities	3/50
	Investments	• Capital invested in sustainable solutions • Capital dis-invested from carbon intensive assets	Investments associated with CSC activities	15/50
Environmental	Emissions equivalent	• CO_2-eq per functional unit • Absolute CO_2-eq	CO_2 eq. emissions associated with the supply chain	44/50
	Energy Usage	• Energy intensity • Cumulative energy use • Energy from renewable sources	Energy-based indicators associated with the supply chain	44/50
	Water	• Water used • Wastewater production • Discharges to water	Water used or contaminated	42/50
	Waste	• Waste sent to landfill • Waste recovered	Residual waste produced or recovered by supply chain activities	36/50
Social	Social Impacts associated with CSC	• 'Green' jobs created	Employment opportunities provided by the CSC	4/50
CE	Overall Circularity	• Global CE Score • Parts Collected and Remanufactured	Indicators of environmental awareness of the customers	3/50

Table 8
Calculation of the normalised weights for the dimensions.

	Occurrences (%)	Normalised dimension weight
Economic	80%	0.49
Environmental	66%	0.40
Social	18%	0.11

Table 9
Calculation of the normalised weights for the economic indicators.

	% articles	Normalised indicator weight (0.49 Economic dimension weight)
CSC Cost	52%	0.31
CSC Profit	22%	0.13
Time Responsiveness	8%	0.05

on the basis of the relative frequencies, in analogy with the calculations shown for L-CEI.

The environmental component is dominant (Fig. 14), and accounts for more than half of the total weight. The most important metrics are mainly carbon-based and energy-based measures, not differing from the ones which can be found in the sustainable supply chain management literature, with no specific emphasis on circularity issues. A considerable weight large portion (0.21) is also attributed to a water consumption measure. Among the economic indicators, considerable importance is given to investments to support the transition towards a more CE, both through sustainable interventions (0.15) and through disinvesting from polluting and carbon intensive solutions (C-I-S) (0.09). Revenues from "green" products refers to the sale of sustainable or remanufactured products and services. The Social dimension has a slightly lower weight than in the L-CEI (0.06) and includes a single indicator (the amount of 'green jobs' created).

5. Discussion

The objective of this section is to critically assess findings which have been reported. The first subsection compares the academic and the industrial literature. Then, a underlying assumptions of DSTs and CE indicators are analysed in detail. The advantages and the disadvantages of different approaches to multidimensional decision making are discussed, together with some promising research avenues.

5.1. Comparing CE indicators from the literature and the industrial practice

The first aspect that emerges is that DSTs in the literature and Corporate Sustainability reports place emphasis on different aspects and metrics. L-CEI, which represents the most common metrics selected in DSTs in the literature, seems to over-represent economic measures. On the other side, practitioners measure more often positive environmental effects of CE practices, focusing on the energy consumption of the supply chain, and on its dependence on carbon intensive sources. Also, they integrate more often circularity metrics, which develop mass balances between inputs and outputs in the production system (Walker et al., 2021b).

A possible explanation of these differences might have to do with the different scope of sustainability reporting and DSTs. DSTs most of the times look at the implementation of new CE practices, which require evaluating economic aspects and to define a business case for the organisation and the supply chain. Differently, Corporate Sustainability reports perform a consumptive evaluation of already implemented CE practices (usually referring to the previous financial year). Despite the lack of standard reporting approaches (Opferkuch et al., 2021), CE practices are expected to reduce organisations' impact on the environment; stakeholders might require this type of evidence in reports (Howard et al., 2019).

Both the indexes (L-CEI and I-CEI) show that existing frameworks and selected metrics struggle to fully capture the adherence of supply chains to the CE paradigm. Materials' circularity indicators are included only in rare cases and environmental aspects are often restricted to very simplified indicators, usually based on the cumulative carbon emissions of the supply chain. This choice might derive from knowledge that is consolidated in SSCM discipline: the operationalisation of reverse logistics feedback loops require the activation of facilities (such as processing and disassembling centres, along with remanufacturing plants) and, possibly additional transportation flows (Helander et al., 2019). All these activities employ resources, energy, and cause emissions in the environment and could give rise to rebound effects (promoting, overall, higher resources consumption rates) (Zink and Geyer, 2017). However, in a CE, supply chains should work in a radically different way and try to consider alternative strategies to reduce waste streams.

I-CEI economic metrics are mainly representative of revenue flows related to 'circular' products. This can be explained as, at the moment Industrial Organisations are not adopting CE practices across the whole supply chain, but just in some niches. As such, the current indicators are not designed to measure the performance of a whole CSC, but just some

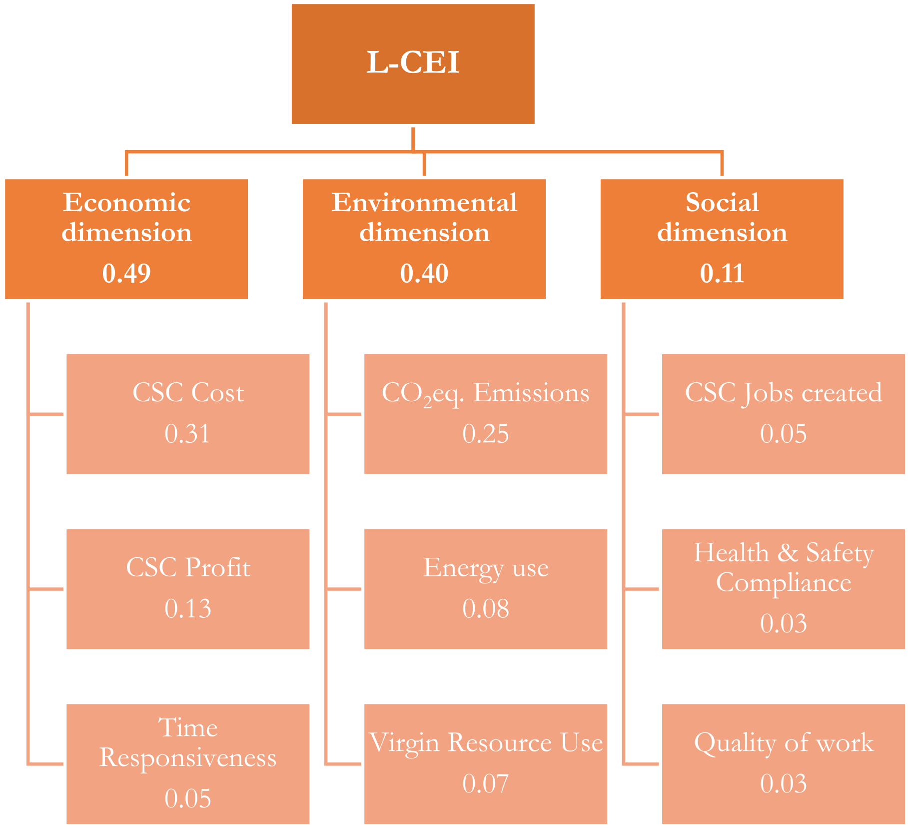

Fig. 13. A literature-based CE indicator.

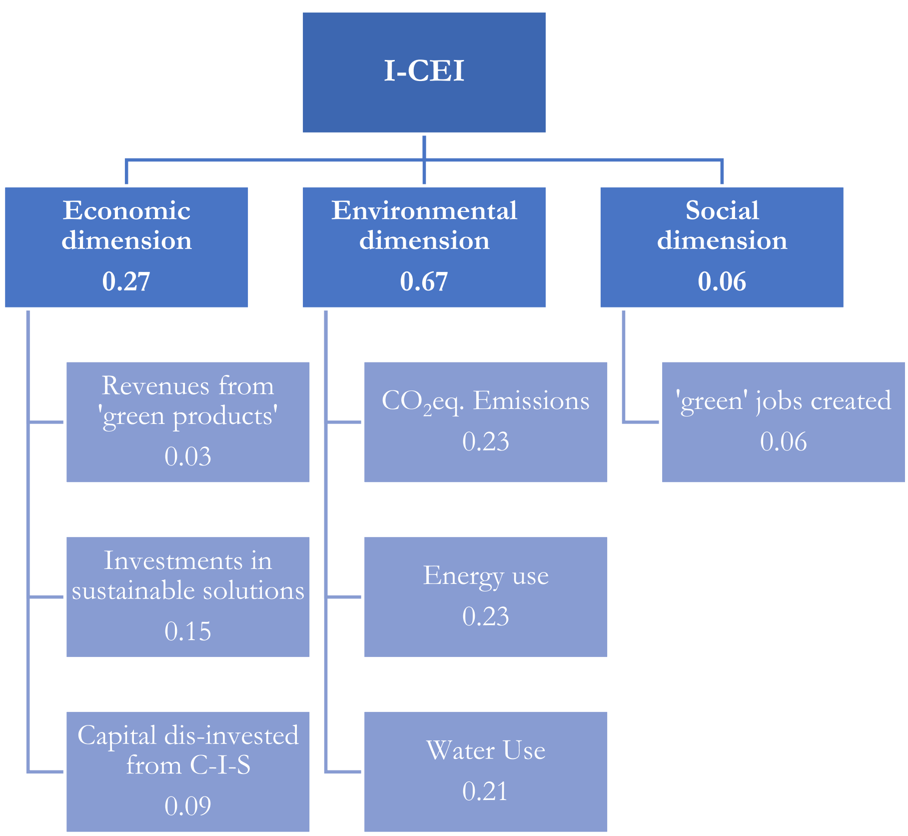

Fig. 14. An industry-based CE indicator. CIS: Carbon Intensive Solutions.

parts of it. Some of the possible metabolisms, where products and materials are used multiple times, are not measured. Rather, DSTs concentrate on a few metabolisms related to recycling, where the products and the waste of linear productions consumption systems are recovered and down-cycled. Measuring multiple feedback loops and metabolisms would tell something more about how much methods of production are self-sustaining and less dependent on primary materials, as well as how much primary production has been displaced with the adoption of CE-related practices.

Both the indexes similarly have a low consideration of social indicators, which confirms previous literature claims (Walker et al., 2021a).

5.2. Reductionism in decision support tools for circular supply chains

The results section 4.3 shows that DSTs systematically select some metrics and ignore others. These choices are not just technical, but also constitute an important decision, in terms of value perception and worldview assumptions.

DSTs in the CSCM domain need to be simple and easy to use, as decision makers need to understand and support the resulting decisions to design and transform existing supply chains. Simplification concerns many aspects that have already been mentioned (selection of metrics, and their aggregation) and some others, like the temporal horizon, considered the type and number of objectives or actors included in the decision. A single indicator is often chosen as a proxy of all environmental (or social) impacts. As a consequence, DSTs have a reductionist interpretation of what to measure to support decisions, and as a consequence of what sustainability is and on what a CSC should be.

A second aspect of reductionism in the academic literature of CE indicators concerns how DSTs deal with trade-offs among different variables. Most of the time, models accept some increase of negative impacts if that allows some type of benefit. This is quite a strong assumption, as variables belonging to different sustainability dimensions have complex relations and dependencies, which cannot be easily described by some linear parameters. *Composite indicators* represent an extreme case aggregating metrics from different dimensions into a single unit-less number. *Monetary tools* transform many variables in to monetary terms, even natural or social ones. Also *Biophysical tools* are not exempt from doing some approximations: carbon equivalent emissions (CO_2-eq.), which represents the most commonly used indicator, is a linear combination of different greenhouse gases and their global warming potential. Non-compensatory *multi-criteria* approaches can provide a solution to this; their main advantage is that, by avoiding simplistic aggregations, they are less affected by a reductionist perspective (Martinez-alier et al., 1998). However, also these approaches might not be free from problems: sometimes a single indicator is used as a proxy of all the possible indicators within one sustainability dimension; in other cases composite indicators are created for each sustainability dimension as linear combinations of some selected metrics. This could lead to the same problems highlighted for composite indicators (e.g. loss of meaning).

5.3. Different pathways towards CE measurement in supply chains

DSTs are not always transparent and open on value assumptions behind the models. Both the conceptual choices (e.g. what metric to select and what to ignore) and the methodological ones (whether to aggregate or normalise or not and with what weights) behind each DST are never neutral or objective. They are inspired by embedded worldviews, which are linked to a certain idea of *value*. These underlying value assumption have an impact on guiding decisions towards different paths of adoption of the CE in supply chains. The recent debate on the CE acknowledges different circular futures are possible (planned circularity, circular modernism, bottom-up sufficiency, peer-to-peer circularity) (Bauwens et al., 2020). The way the transition towards the CE is measured will impact the design of transition pathways to future scenarios, and the resulting supply chains. In fact, indicators act as value-articulating institutions, enforcing a very specific worldview and set of values, which should at least be acknowledged (Gasparatos and Scolobig, 2012).

The classification presented in Section 4.1.4 groups DSTs according to underlying value assumptions. The following paragraphs explore these differences, along with the advantages, the disadvantages of each class of tools (Table 10). Different pathways towards CE measurement in supply chains are recognised, according to what desired outcome of change can be measured by the tools.

Monetary DSTs for CSCs adopt a neoclassical perspective of value and do not challenge the assumptions and the "rules of the game" in today's free-market economies (even without mentioning it openly). In free-market economies actors are driven by economic benefits and companies act as profit maximisers (Martinez-alier et al., 1998); what is right or wrong is decided by subjective preferences and an anthropocentric valuation system that focus on utility functions and consumer preferences in a market setting (Martinez-alier et al., 1998). Also, nature and environmental impacts are monetised and included in market transactions. Markets have a key role in guiding the transition towards CSCs.

These DSTs usually provide whole-supply chain visibility of the processes and materials involved in the manufacturing process, as well as different actors' preferences and utility functions. As such they are able to present the different economic incentives for each CSC actor involved in the value creation process. These models estimate how much it costs to set up reverse channels to recover end of life products and how much additional revenues (or avoided investments) different CE practices can help to generate. Modelling CE benefits and negative impacts across more dimensions and more supply chain stages could show under which condition establishing a CSC is profitable.

As such successful CSCs are systems that use recycling and other CE strategies to increase the efficiency they have in using materials, are able to create economic value for their customers through the adoption of some CE practice, are able to use reverse logistics to recover "linear" products at the end of their life, and thus consume less resources and produce less waste. As these DSTs come mainly from an engineering background, they consider a CSC as a system that should work efficiently, without considering the socioeconomic context in which they operate (Zink and Geyer, 2017). This view usually implies reductionist views of sustainability and of the CE. These supply chains might use

Table 10
Advantages and Disadvantages of different classes of articles in the literature.

Type of tools	Advantages	Disadvantages	CSC desired evolution
CSC Monetary tools	Detailed evaluation of flows among SC stages; estimation of actors' utility functions	Lack of ability to highlight the systemic impacts of CSC on the environment and society	CSCs that are able to close the loop; focus on efficiency
CSC Biophysical tools	Can determine with precision the environmental impacts of CSCs	Sometimes unable to measure and visualise the CE potential related to regenerative flows of resources as not always employed measures explicitly account for circularity	CSCs that consume less resources and work in symbiosis with the Nature
CSC Composite and multi-criteria indicators	useful to consider and integrate multiple stakeholders' perspective	the outcome of the analysis might depend exclusively on technical decisions (weights)	Flexible; it depends on involved decision-makers, weighting and normalising procedures

materials more efficiently or not (this is not often measured). The risk of a rebound effect and of market barriers to the operationalisation of CE practices is usually not part of the models. Desirable CSCs do not necessarily produce less products, but more products with a lower amount of inputs per unit of product.

Biophysical DSTs incorporate an *eco-centric* perspective of value. Monetary incentives and supply chain actors' preferences and utility functions are usually not part of these models. What is right or wrong to produce is decided by the cost and the impact of production. Production and consumption systems are considered in close relationship with Nature, as an active and integrative part of it. They measure the flows between economic systems and natural ones and look at how much resources are consumed, how much waste is created, how much emissions and environmental impacts are caused.

These tools are able to compare different products and configurations of reverse supply chain along with value retention strategies. Alternatives are compared according to the environmental cost of their production and to how heavily they depend on Nature. As such, the amount of primary resources a CSC uses for the production of goods should be minimised. Successful CSCs are systems that are able to decouple production from consumption of resources in absolute terms. Biophysical tools can provide an accurate estimation of environmental impacts thanks to a life-cycle perspective. This can help CSC decision-making processes to move away from the mainstream perspective of accounting just for the economic cost of production of goods and services. Furthermore, they can also provide insights on how to measure and visualise the CE potential related to regenerative and restorative flows of resources in supply chains, in order to re-use material flows and waste as a resource according to an Industrial Ecology view. However, currently selected indicators are more concerned with traditional environmental impact measures rather than with metrics that could evaluate the circularity potential.

Composite and multi-criteria approaches do not rely on a pre-defined conception of value; this depends on selected sub-indicators and on specific aggregation procedures. It can be more eco-centric or more anthropocentric. Also, in SCM environments, composite indicators are rather common, both among researchers and practitioners. CSCs provide an ideal theoretical and practical context in which these methods could support decision-making. In this complex context, a wide range of stakeholders inside and outside the supply chain may be interested in evaluating the performance of the CSC using an established and standard model. *Composite and multi-criteria* approaches can combine the strengths of the previous classes of tools. The main advantage provided by such approaches is the ability to summarise complex and multi-dimensional phenomena for supporting decision-makers. Such methods are particularly effective in contexts in which multiple stakeholders are involved. However, normalisation and aggregation might cause loss of details and meaning (Martinez-alier et al., 1998).

In general, the main worldviews in supply chain management might have a role in influencing the type of transition towards the CE (Nieuwenhuis et al., 2019). Values assumptions affect how the tools are designed and as a consequence also the prescriptions resulting from the analysis (Saltelli et al., 2020). The majority of the DSTs for CSCs (even without stating it openly) adopt a neoclassical perspective of value and do not challenge the assumptions and the rules of the game in today's free market economies (Korhonen et al., 2018). By doing so models enforce and promote this worldview, mainly focusing on efficiency gains over more innovative supply chain configurations that could include radical changes in the use phase, ownership of products. The outcome could be production systems that are circular, making use of a lot of recycled materials flows, but still consume a lot of resources and energy.

For these reasons, it is important to discuss the underlying objectives of the transition towards a CE. Incorporating other worldviews means making a reflection on consumerism, on the desirability of the growth paradigm and on the effectiveness of free market settings for some goods. This discussion is part of a wider political debate, which includes the need to update GDP as a measure, integrating it with some other metrics and perspective. It includes a reflection on the role of firms and of other institutions to deliver more sustainable production and consumption systems.

5.4. Contribution to theory and practice

This study contributes to theory by reviewing already developed CE indicators at the supply chain level, which were not reviewed until very recently (Walker et al., 2021b). Previously CE indicators and metrics were reviewed only at the single firm level of analysis and no SLR had focused on CE indicators at the supply chain level. This review confirms some of the results and considers many papers that were not included in previous literature reviews (Sassanelli et al., 2019a; Vinante et al., 2021). By identifying indicators and extracting metrics from decision support tools this paper connects streams of literature (or topics) that seems to be disconnected, e.g. SCM literature focusing on CLSCs, and CE literature.

A second theoretical contribution of this paper consists on reflecting critically on the choices behind tools definition and indicators selection. This literature identifies the value assumptions behind the choices that characterise the creation of tools and indicators, as suggested in sustainability science literature (Gasparatos and Scolobig, 2012). DSTs supporting CSC decision making will determine how the transition towards the CE in production and consumption systems will happen and define the type of CE economy our societies will achieve. By recognising the different paths of evolution of supply chains from a linear configuration to a circular one, this paper aims to contribute to this discussion.

This paper contributes to practice by putting together all the CE indicators that have been developed and included in existing DSTs for supply chains. Two first prototypes are proposed to summarise existing knowledge for practitioners.

6. Conclusions

This paper has aimed at investigating CE indicators in the context of CSCM literature as well as those found in company Corporate Sustainability reports and represents a first step towards the development of decision support tools for designing and evaluating CSCs. Two CE indicators prototypes are proposed with the objective of summarising the most frequent choices in current models in the academic and practitioners' literature.

The analysis reveals that current indicators in the literature focus mostly on measuring the negative environmental impacts of CSCs and seldom incorporate metrics aimed at evaluating the economic and environmental potential behind the circulation of resources. The most frequently employed metrics are carbon emissions, the use of energy and economic cost. DSTs in the literature evaluate economic aspects more frequently than Corporate Sustainability reports, which measure more often environmental aspects. Both the literature and the industrial practice show a simplified and superficial consideration of social implications in measuring the transition towards the CE in supply chains.

The paper also argues that the approaches in the CSCM literature have a reductionist interpretation of sustainability aspects. Single metrics are selected to represent whole sustainability dimensions, arbitrary weights are chosen, strong assumptions are made, such as that environmental and social impacts can be converted into monetary terms. The three different classes of tools identified reflect very different assumptions and worldviews and as such can drive different pathways of evolution of supply chains from a linear configuration to a circular one. CSC Monetary tools focus on improving the economic efficiency of production and consumption networks through the adoption of CE practices; CSC Biophysical tools aim at developing CSCs that consume less resources and work in symbiosis with the Nature; composite and multi-criteria approaches heavily depends on involved decision-makers, aggregation, weighting and normalising procedures.

Future research in SCM should clearly state value assumptions of the models and challenge the prevalent configurations and beliefs to explore how the CE can deeply transform production and consumption systems.

6.1. Limitations and future research directions

A first limitation of the presented work could arise from the different scope of practitioners' and academic literatures, which might make the comparison problematic. The former deals with reporting consumptive results for stakeholders; the latter with the creation of tools that most of the times are used both to support decisions in the design phase and to evaluate existing production and consumption networks. For this reason, more research is needed to confirm these findings.

A better CE indicator could be built through a more comprehensive and structured application of MCDM methods and involvement of stakeholders and experts from a variety of backgrounds (academia, industry, NGOs, national and local government). These actors could rigorously choose a subset of representative indicators as well as the relative weights. Selected CE Indicators might also be kept separate in order to avoid the disadvantages of composite indicators. The use of Principal Component Analysis (PCA) could also help to identify a subset of indicators that are independent of one another and develop a more robust and effective index. Secondary datasets could be utilised for this purpose, such as Ecoinvent (2018)[6], a life cycle inventory database that associates detailed environmental impact indicators across all the phases of the life of a product; essentially, such database provides a big repository of bill of materials for specific products and processes, along with associated environmental impacts and estimates of resource consumptions.

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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