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Mapping and testing circular economy product-level indicators: A critical review

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A B S T R A C T

Numerous indicators have been suggested as tools for assessing progress towards the circular economy (CE). However, it is unclear what specifically is captured by CE indicators and few studies have tested them on real cases. This review addresses this gap by describing and comparing the resource-related effects captured by existing resource-based product-level indicators and suggesting recommendations for their use and further development. First, the flows and processes quantified by product-level indicators are mapped on a novel flowchart model, which can also be used to select and develop indicators. Second, the indicators are tested on seven real cases. Third, indicator and life cycle assessment (LCA) results are compared. A significant divergence of indicators' scope is found, where most capture a limited part of the product system. Moreover, important aspects of the CE are not captured: no indicator accounts for resource use in the use phase and there is limited attention to lifetime extension strategies. Additional limitations are the difficulties to assess multiple use-cycles and that most indicators cannot capture absolute mass variations, thus neglecting mass reduction strategies. The testing reveals that using a set of single-focus indicators may be necessary to outline trade-offs. Multi-focus indicators are sometimes harder to analyse but provide a more comprehensive assessment. The testing also illustrates that indicator and LCA results are not necessarily aligned. The latter provides information on environmental impacts and can point to trade-offs between impact categories such as climate change, resource use and land use, indicating that CE indicators cannot easily replace LCA.

1. Introduction

The concept of circular economy (CE) has gained popularity in recent years as a means for increasing companies' competitiveness and reducing the environmental footprint of society (Geissdoerfer et al., 2017). The CE proposes a regenerative production system where resource cycles are closed and the embedded value is utilized for as long as possible through, e.g. closed loop value chains, circular business models, and design for longevity (Ghisellini et al., 2016). In the literature, the CE is viewed as an umbrella concept (Blomsma and Brennan, 2017) for which no consensus has yet been reached regarding its definition (Kirchherr et al., 2017), nor for the terminology of the many strategies related to its operationalisation (Reike et al., 2018). In this study, the typology of physical measures for the CE developed by Böckin et al. (2020) is used, henceforth referred to as "CE strategies". This typology has the benefit of outlining physical CE strategies that can be undertaken at different phases in a product system. The typology is organised around four main groups of CE strategies, i.e. those targeting: 1) extraction and production, 2) effective and efficient use of products, 3) extended use of products, and 4) end-of-life. These could be implemented in combination to achieve the systemic change aimed for by the CE, e.g. with strategies targeting different life cycle phases.

Since the CE points to numerous opportunities for extending resource life, it is challenging to understand how resource use may be affected and, as a result, to decide on the appropriate strategies to implement. Consequently, a transition towards a more circular economy needs to be supported by quantitative assessment frameworks for monitoring changes and supporting decision making. Comprehensive and systemic methods such as life cycle assessment (LCA), for analysing the environmental impact of products and services, or material flow analysis (MFA), for analysing stocks and flows of materials, are already used for this purpose (Corona et al., 2019; European Commission, 2018). However, they have the disadvantage of being time and resource consuming. Comparatively, indicators have the advantage of being easier to compute and communicate. Multiple indicators for the CE (henceforth referred to as indicators or CE indicators) have already been developed

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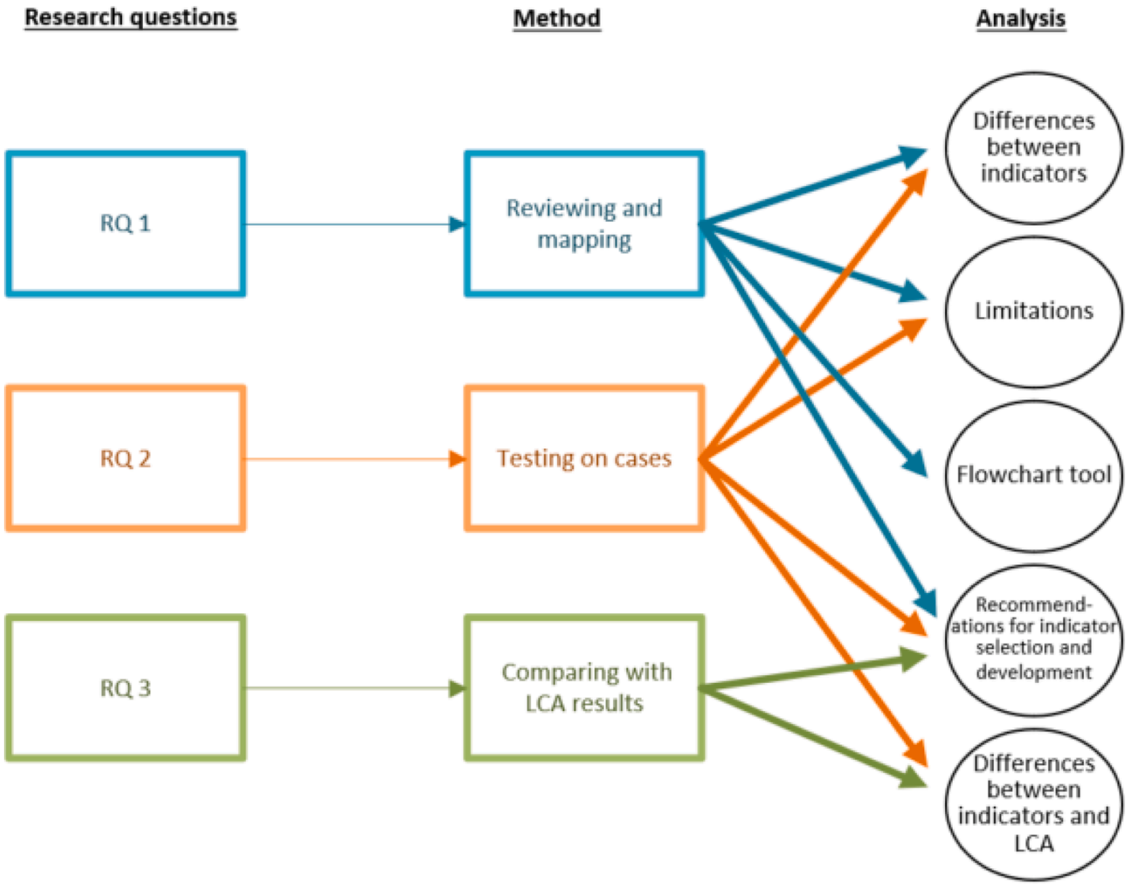

Fig. 1. Overview of the research questions, method, and structure of the analysis.

covering different levels and aspects, such as global material recirculation (de Wit et al., 2020), decoupling of the material footprint from economic growth (Oberle et al., 2019), or regional innovation and investment (European Commission, 2018).

For companies, regarded as essential actors in the transition to a more circular economy (Lieder and Rashid, 2016), indicators are useful tools for both internal purposes, such as monitoring progress or assessing potential changes to product portfolios, and for external purposes, such as benchmarking and communicating with customers and suppliers (Saidani et al., 2019). Assessment at the product level is key for both usages. Previous reviews of product-level indicators revealed that there is no standardised way of measuring the CE (De Pascale et al., 2021) and that most indicators have a limited focus in terms of the CE strategies addressed (Kristensen and Mosgaard, 2020), sustainability aspects (Corona et al., 2019; Kristensen and Mosgaard, 2020), or life cycle phases covered (Helander et al., 2019). A common recommendation is to use of a set of indicators to ensure a wide coverage of CE strategies (Corona et al., 2019; Moraga et al., 2019) but further research is needed to identify the complementarity between existing CE indicators (Parchomenko et al., 2019; Saidani et al., 2019) and between CE indicators and other existing assessment frameworks such as LCA (Corona et al., 2019; Helander et al., 2019).

The conclusions of previous reviews are often drawn from an analysis of the indicators' methodology descriptions, based on various classifications. Only one previous review tested indicators on a case to identify "desired and required features for an efficient and effective" CE assessment for product design (Saidani et al., 2017a, p.6). The authors concluded that the three indicators tested, i.e. the material circularity indicator (MCI) (Ellen MacArthur Foundation and ANSYS Granta, 2019), circular economy toolkit (CET, not available anymore) and circular economy indicator prototype (CEIP) (Cayzer et al., 2017), were too superficial and unable to grasp all CE strategies. Previous studies have also attempted to apply CE indicators on case studies and to compare or combine the results with LCA. Walker et al. (2018) examined the application of the MCI, CET, and CEIP indicators with LCA results on a tidal energy device, and Niero & Kalbar (2019) combined insights from indicators (MCI and material reutilization score (C2C) (Cradle to Cradle Products Innovation Institute, 2016)) and LCA to analyse beer packaging. LCA results have also been compared with the MCI for recycling of used tires (Lonca et al., 2018), with the product circularity indicator (PCI) for a washing machine (Bracquené et al., 2020), and with the C-metric for various products (Linder et al., 2020). These studies highlighted a difference in the selection of preferable CE strategies for a given product compared to conclusions from LCA results (Walker et al., 2018) and the difficulty of applying a CE indicator on complex products (Linder et al., 2020). However, the range of tested indicators remains limited, hindering a deeper understanding of what they de facto measure. This knowledge is believed to be crucial in the development of measurement frameworks (Meadows, 1998).

This article aims to clarify what resource-related effects from implementing CE strategies are captured by existing product-level indicators. The contributions of this study are threefold. First, the broadness of the CE concept and the lack of consensus on its definition and its measurement has led to unclarities on what CE indicators specifically quantify along the product system. This gap is addressed by reviewing existing resource-based CE indicators and by developing a detailed flowchart tool, representing the processes and resource flows the indicators account for. Second, since few studies have tested CE indicators, it is not clear how their results differ when assessing the same case and what their limitations are from a resource perspective. This gap is addressed by testing the indicators on seven real cases that combine multiple CE strategies. Both the flowchart tool and the testing thus

Table 1

List of cases (BAU cases in grey) and their related CE strategies (Böckin et al., 2020) used for testing CE indicators.

Study	Case	Brief description	CE strategies			
			Extraction and production	Use effectively and efficiently	Extend use	End-of-life
Incontinence products	a. Recycled production wastes	All manufacturing wastes are incinerated. Products are collected for incineration at end-of-life, except for the packaging which is recycled.				Recycling Energy recovery
		All manufacturing wastes are sorted and recycled back into production. Products are collected for incineration at end-of-life except for the packaging which is recycled.	Reducing losses in production			Recycling Energy recovery
	b. Change to bio-based material	Absorbing pad with 63% renewable material. Products are collected for incineration at end-of-life except for the packaging which is recycled.				Recycling Energy recovery
		Absorbing pad with similar absorption with 73% renewable material. Products are collected for incineration at end-of-life except for the packaging which is recycled.	Changing material in product			Recycling Energy recovery
	c. Multiple use	A single-use all-in-one underwear and absorbing product. Products are collected for incineration at end-of-life except for the packaging which is recycled.				Recycling Energy recovery
		Reusable pants (washed and reused 20 times) combined with a disposable absorbing pad. Products are collected for incineration at end-of-life except for the packaging which is recycled.			Shift to multiple use	Recycling Energy recovery
	d. Effective use	Choice of size and absorption capacity by the user. Products are collected for incineration at end-of-life except for the packaging which is recycled.				Recycling Energy recovery
		Size and absorption capacity are tailored to the user's measured urinary leakage, leading to lower material requirements while maintaining the hygiene function. Products are collected for incineration at end-of-life except for the packaging which is recycled.		Use effectively		Recycling Energy recovery
Laptop	e. Reused laptop	Laptops are used for 3 years. Then, 50% of laptops are collected for recycling. The fate of the remaining 50% is highly uncertain but modelled to be sent to controlled landfill.				Recycling Energy recovery Landfill
		A resale company collects 3-year-old laptops, deems 70% of them to be reusable for another three years, and sends the remaining 30% to recycling. After their second use, 50% of laptops are collected and sent to recycling.			Using more of technical lifetime (incl. reuse)	Recycling Energy recovery Landfill
Truck engine	f. 3D-printed engine	Conventional engine shredded at end-of-life with the major recyclable metal fractions recycled. Fuel consumption during use is included.				Recycling Landfill
		20% of the engine is 3D-printed with aluminium and stainless steel, replacing aluminium, cast iron and low-alloy steel parts, and reducing the engine weight by 6%. Fuel consumption during use is included. The engine is shredded at end-of-life with the major recyclable metal fractions recycled.	Reducing material quantity in product Changing material in product	Reducing use of auxiliary materials and energy		Recycling Landfill
	g. Advanced 3D-printed engine	Same as case f.				Recycling Landfill
		80% of the engine is printed with low-alloy steel, leading to a weight reduction by 22%. Fuel consumption during use is included. The engine is shredded at end-of-life with the major recyclable metal fractions recycled.	Reducing material quantity in product Changing material in product	Reducing use of auxiliary materials and energy		Recycling Landfill

provide guidance for interpreting, selecting, and developing CE indicators. Third, few studies have compared CE indicator results with those from LCA, and only for a limited number of indicators. This gap is addressed by comparing LCA and CE indicator results for a wide range of indicators, investigating whether the conclusions drawn from the two methods differ. Note, however, that the focus is on critically reviewing the indicators and not on assessing the cases.

Consequently, the following research questions are investigated (Fig. 1):

1) What resource flows and processes are captured in CE indicators?
2) How do indicator results differ when applied to the same case and what limitations can be identified?
3) Do the conclusions drawn from CE indicators differ from those drawn from LCA?

This study focuses on material resources since: 1) resources are a key component of the CE, which have been argued to have an overarching aim of, e.g. extending the productive life of resources (Blomsma and Brennan, 2017), retaining resource value (Reike et al., 2018), or closing, slowing, and narrowing resource loops (Bocken et al., 2016), and 2) resource use is arguably connected to environmental performance (Steinberger and Krausmann, 2011), a key target of CE implementation (Kirchherr et al., 2017).

2. Method

The method applied in the study consists of three steps: 1) conducting a systematic literature search of existing indicators for the CE and analysing the resource flows captured by these on a novel flowchart model, 2) testing the indicators on seven cases representing a range of

Table 2
Indicators in the review. Abbreviations: RL, reducing production losses; MC, changing material composition; RU, using more of technical lifetime (incl. reuse); Rem, remanufacturing; Rec, material recycling; ER, energy recovery; L, increasing technical lifetime by design; E, extraction; MP, material production; M, component and product manufacturing; U, use; EOL, end-of-life.

CE strategies	Name	Life cycle phases					Function	Time	Energy	Renewables	Reference
Reducing losses in production											
RL	EI	E	MP	M					X	X	(Lokesh et al., 2020)
RL	FI		MP	M							(Lokesh et al., 2020)
RL	PMC		MP	M							(Lokesh et al., 2020)
RL	WF	E	MP	M							(Lokesh et al., 2020)
Changing material composition											
MC	PR		MP							X	(Lokesh et al., 2020)
MC	RC		MP	M							(Graedel et al., 2011)
MC	RCR		MP	M							(Ardente and Mathieux, 2014)
Using more of technical lifetime (incl. reuse)/remanufacturing											
RU, Rem	PRI-reuse			M	U						(Mesa et al., 2018)
RU, Rem	Rreuse			M		EOL					(Ardente and Mathieux, 2014)
Material recycling											
Rec	CR					EOL					(Haupt et al., 2017)
Rec	EOL-RR					EOL					(Graedel et al., 2011)
Rec	LRR					EOL			X		(Marvuglia et al., 2018)
Rec	OSCR					EOL					(Graedel et al., 2011)
Rec	OSR		MP	M		EOL					(Graedel et al., 2011)
Rec	PRI-rec			M		EOL					(Mesa et al., 2018)
Rec	RBR	E				EOL			X		(Marvuglia et al., 2018)
Rec	RPER					EOL					(Graedel et al., 2011)
Rec	RR					EOL					(Haupt et al., 2017)
Rec	Rrec			M		EOL					(Ardente and Mathieux, 2014)
Rec	RYR					EOL			X		(Marvuglia et al., 2018)
Energy recovery											
ER	Rrecov			M		EOL					(Ardente and Mathieux, 2014)
Multi-focus											
Rec, RU, Rem	C				U	EOL					(Figge et al., 2018)
MC, Rec	C2C		MP			EOL				X	(Cradle to Cradle Products Innovation Institute, 2016)
RL, Rec, ER	CEV		MP	M		EOL			X	X	(Fogarassy et al., 2017)
RL, Rec	CI	E	MP			EOL			X		(Cullen, 2017)
RL, Rec	CPEI	E	MP	M		EOL			X	X	(Lokesh et al., 2020)
RL, Rec	CPFI		MP	M		EOL					(Lokesh et al., 2020)
RL, Rec	CPWF	E	MP	M		EOL					(Lokesh et al., 2020)
RL, Rec	LFI2		MP	M		EOL					(Mesa et al., 2018)
RL, Rec	RE-EEE	E		M	U	EOL					(Juntao and Mishima, 2017)
Multi-focus with function/time included											
RU, L, Rec, Rem	L				U	EOL		X			(Figge et al., 2018)
RL, RU, L, Rec, ER	MCI		MP	M	U	EOL	X	X		X	(EMF, 2019)
RL, RU, L, Rec, ER	MCI-BB		MP	M	U	EOL	X	X		X	(Razza et al., 2020)
RL, RU, L, Rec	PCI		MP	M	U	EOL	X	X			(Bracquené et al., 2020)
RL, L, Rec	SERI	E	MP		U	EOL	X	X	X		(Winzer et al., 2017)
RL, Rec	RNL	E	MP	M	U	EOL	X	X			(Ljunggren and André, 2019)

CE strategies, and 3) comparing the indicator results and LCA results for the same seven cases.

2.1. Review and mapping of CE indicators

2.1.1. Systematic literature search

A list of existing product-level CE indicators was compiled based on a systematic literature search in the Scopus database with a combination of key words such as *indicator, metric, score, measur*, index, circular economy* or *resource efficiency*. A screening process of the 422 database entries that were found was performed to exclusively select indicators, or sets of indicators, tailored for products, components, or materials, which resulted in 27 entries. Grey and scientific literature found in the reference list of the reviewed documents were included in this process (snowballing), resulting in the addition of 14 relevant entries.

A second selection based on the analysis of data requirements for the indicators' calculation was performed to select resource-based indicators suitable for further analysis. It ensured that indicator methodologies were available, free from subjective or economic inputs, and were easier to perform than time and data intensive environmental assessment frameworks such as LCA. Detailed information on the reasons for removing indicators from the selection is available in the Supplementary information, section S.1. Finally, 36 indicators from 16 publications were kept for further analysis.

2.1.2. Indicator review

To map the parts of the product system that indicators capture, a flowchart model was constructed. An in-depth analysis of the data requirements, method descriptions, and equations for calculating the indicators revealed the resource flows and related processes they quantify over the life cycle phases of a product system. The flowchart model was constructed in an iterative manner and was continuously extended with new flows and processes as these became apparent over the course of the analysis. This way the model was made as detailed as required to cover the flows accounted for by all selected indicators, while also offering a straightforward comparison of the indicators. To visualize CE strategies and related flows not yet addressed by the indicators, the flowchart model was then further extended with flows and processes related to the CE strategies outlined by Böckin et al. (2020).

Additional aspects of the indicators were then analysed. First, the indicators were grouped according to the CE strategies that their methodology has in focus, based on the 18 physical resource strategies for the CE outlined by Böckin et al. (2020). Second, the life cycle phases each indicator accounts for were determined. This illustrates the extent to which the different parts of the product system are addressed. Third, while all selected indicators require physical resource data, some of

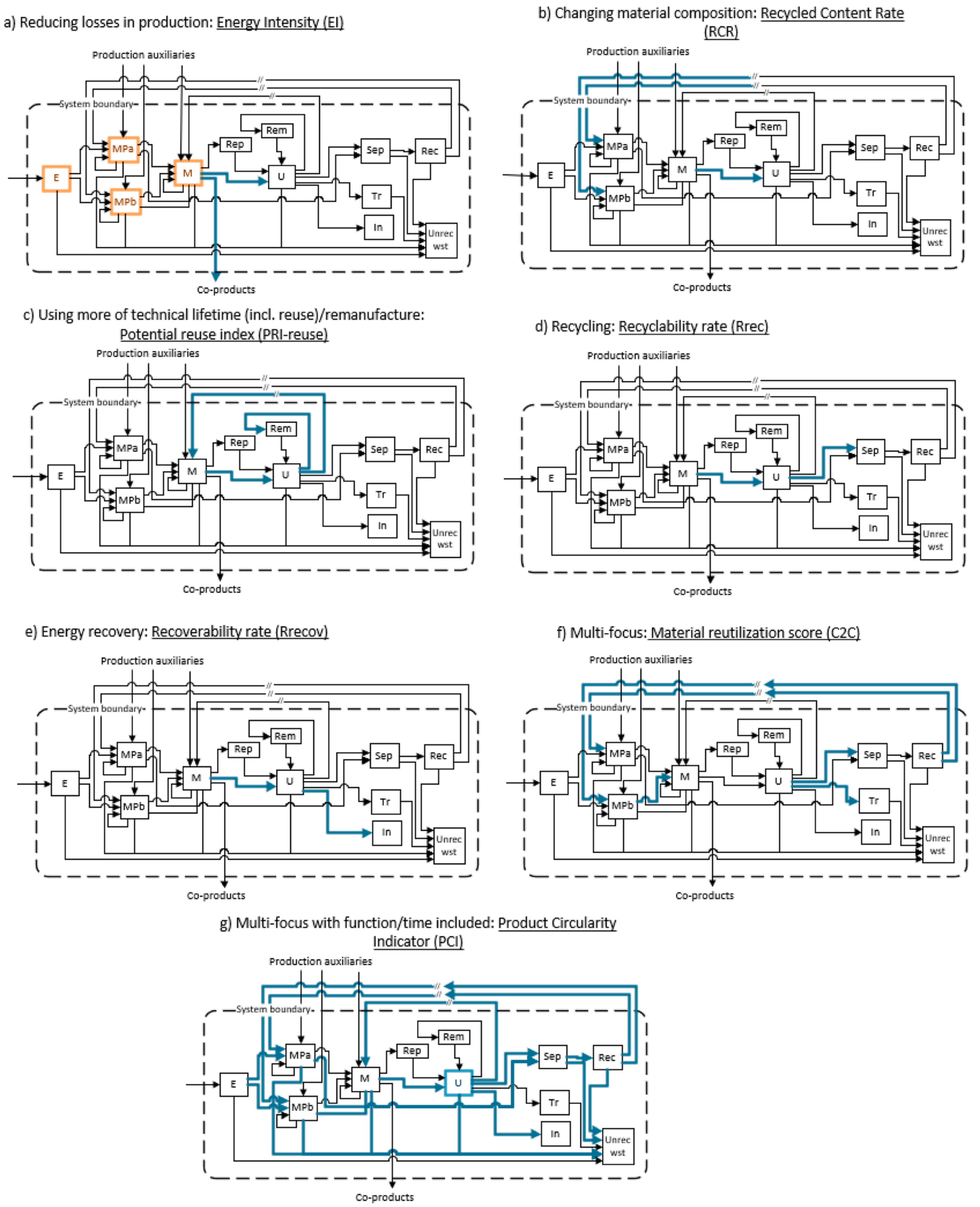

Fig. 2. The flowchart mapping with examples from each group showing flows directly accounted (blue) and not accounted (black) by the indicator. A highlighted blue process indicates some accounting of lifetime/function and a yellow process shows a quantification of energy in that process. Abbreviations: E, extraction; MPa, non-renewable material production; MPb, renewable material production; M, component production and product assembly; Rep, repair; Rem, remanufacturing; U, use; Sep, pretreatment and separation; Tr, biological treatment, In, incineration; Rec, recycling; Unrec wst, other treatment of wastes.

them were found to also make use of additional data. This could be a) data expressing a measure of what a product is used for, i.e. the function provided by the product; b) temporal data that, for instance, indicate the expected lifetime of a product; or c) energy data, e.g. the energy required in a process. Fourth, whether the indicators make an explicit distinction between renewable and non-renewable energy or resources was denoted.

2.2. *Testing of indicators*

To compare the results provided by the reviewed CE indicators, they were applied to three published case studies (André et al., 2019; Böckin and Tillman, 2019; Willskytt and Tillman, 2019), which investigate seven different cases that encompass the complexity of real cases in contrast to many stylised theoretical cases.

The three case studies are: 1) more resource efficient production and use of incontinence products used by care homes residents (Willskytt and Tillman, 2019), 2) lifetime extension of laptops through reuse (André et al., 2019), and 3) weight reduction of a truck engine through 3D-printing (Böckin and Tillman, 2019). For each study, the implementation of CE strategies is compared to a business-as-usual (BAU) alternative, representing the existing situation without the enhanced CE strategies implemented. The BAU alternatives also include some implementation of CE strategies since they reflect a real-life situation where e.g. recycling and energy recovery occur. The cases are briefly presented in Table 1. The case studies cover a range of generic product characteristics identified by Böckin et al. (2020) as important for the outcome of CE strategies. Incontinence products are consumable and disposable products while laptops and truck engines are durable products. Moreover, CE strategies applied in each case are representative of the four groups of strategies highlighted by Böckin et al. (2020) (Table 1).

2.3. *Comparison of CE indicators and LCA results*

For each case, the results of the indicators were compared between the BAU alternative and its related CE alternative(s). As the BAU alternative is the same for both 3D-printing cases, the indicators were then estimated for 13 different alternatives in total. The relative improvement was calculated as the percentage of relative difference between the BAU and CE alternatives if an increase of the indicator value is desirable, and as the opposite of the relative difference otherwise.

LCA results for each case were also expressed in terms of relative improvement and compared to the results of the CE indicators. A set of mid-point impact categories relevant for the cases was selected. For incontinence products, global warming, fossil depletion and agricultural land use were retrieved from Willskytt & Tillman (2019). For the second-hand laptop, results from André et al. (2019) for metal depletion, global warming and ionizing radiation were used. Finally, for the 3D-printed truck engine, global warming and fossil depletion results were retrieved from Böckin & Tillman (2019), and unpublished results for ionizing radiation were added to the study. Information on the impact assessment methods used is available in the Supplementary information, section S.2.

3. Results

3.1. *Indicator review*

Out of the 36 indicators, 21 belong to one of five *single-focus* indicator groups, i.e. they are indicators that focus on one specific strategy (Table 2). 15 indicators were determined to have more than one strategy in focus. They were grouped under the label multi-focus indicators and further divided into two separate groups: indicators that consider lifetime or function in their computation (6 indicators), and those that do not (9 indicators). Fig. 2 shows the flowchart mapping for one indicator per group. The flowcharts illustrate what is directly quantified by each indicator in terms of the resource flows between processes, the energy required or generated in a process, or use phase related aspects like lifetime or provided function. The indicator abbreviations are the same as in the original papers to the extent possible and new ones suggested in cases where no abbreviation was provided by the authors (Appendix A). All 36 flowcharts and indicator formulas are available in the Supplementary information, section S.4.

3.1.1. *Reducing losses in production*

Four indicators focus on *reducing losses in production*: energy intensity (EI) (Fig. 2a), feedstock intensity (FI), waste factor (WF), and process material circularity (PMC) (Lokesh et al., 2020). The EI, FI, and WF are expressed as the energy demand in production, the mass of primary raw material used, and the mass of waste generated in production, respectively, over the total mass of products and co-products produced. Thus, they have a similar approach to measuring the efficiency of production but with a focus on either material input, waste, or energy requirements. The PMC rewards recovery and reuse of process auxiliaries during production and is the only indicator in the selection that accounts for process auxiliaries.

3.1.2. *Changing material composition*

Changing material composition of products is in focus in three indicators, looking either at recycled or renewable content. The recycled content rate (RCR) (Fig. 2b) (Ardente and Mathieux, 2014) is the fraction of recycled material from post-consumer scrap compared to the total mass of a product, while the recycled content (RC) (Graedel et al., 2011) also considers the mass of pre- and post-consumer scrap utilized during production. The product renewability (PR) (Lokesh et al., 2020) is the only indicator that exclusively considers the renewable material fraction of a product.

3.1.3. *Using more of technical lifetime (incl. reuse)/remanufacturing*

The strategy of *using more of the technical lifetime* of a product, i.e. *reuse* by the same or a different user, is in focus for the reusability rate (Rreuse) (Ardente and Mathieux, 2014) and the potential reuse index (PRI-reuse) (Fig. 2c) (Mesa et al., 2018). Their designs make them appropriate for also quantifying reuse of components for *remanufacturing* at end-of-life. Their grouping thus includes two strategies: reuse and remanufacturing. The Rreuse is expressed as the fraction of a product that can be reused. The PRI-reuse is designed for assessments of product families. It compares the mass of reusable components of a product in relation to the total mass of the product family it is a part of, thus focusing on modularity between product variants. For assessments that are not based on product families, it is calculated as the fraction of components that are reusable.

3.1.4. *Material recycling*

The largest group of indicators focuses on *material recycling*. Most of these indicators focus only on the end-of-life phase, e.g. the old scrap collection rate (OSCR) and the recycling process efficiency rate (RPER) (Graedel et al., 2011), which consider recycling system efficiencies in various ways. This is done by taking e.g. collection rates, loss rates, new or old scrap rates into consideration. For instance, the OSCR describes the fraction of material that enters a recycling process at end-of-life, the RPER is the fraction of material recycled over the material entering the recycling process, and the end-of-life-recycling rate (EOL-RR) is the fraction that enters the end-of-life phase compared to the mass of material functionally recycled. Other indicators also account for the manufacturing phase, e.g. the potential recycle index (PRI-rec) (Mesa et al., 2018) and the recyclability rate (Rrec) (Fig. 2d) (Ardente and Mathieux, 2014), which compare the mass that can be recycled to the mass of the finished product. While the former includes an efficiency factor to account for losses during the recycling process, the latter does not.

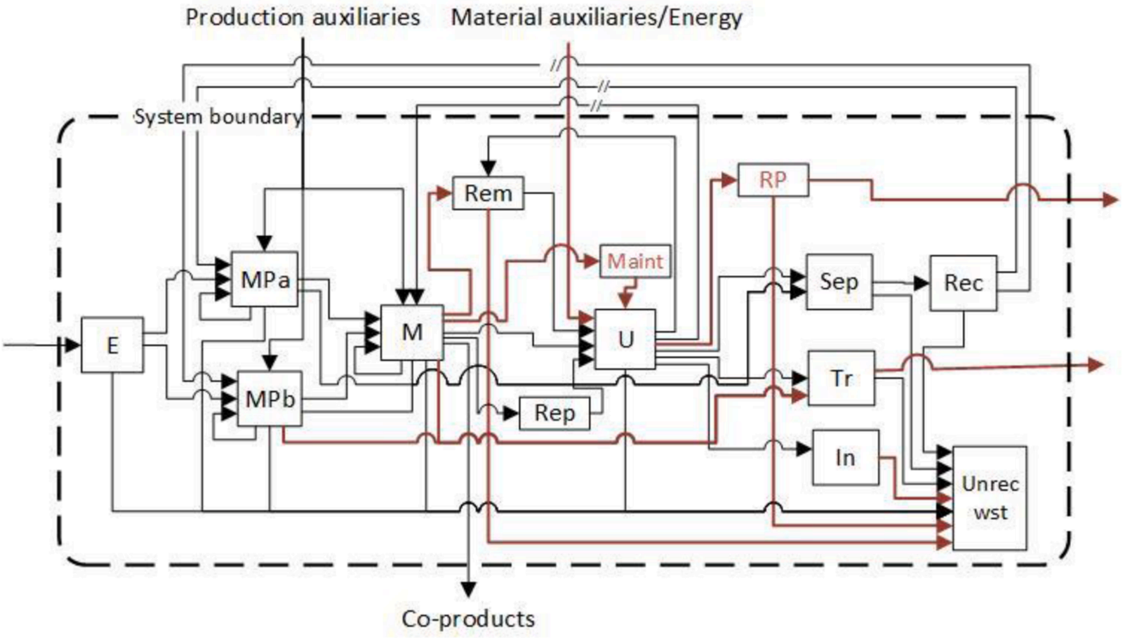

Fig. 3. The extended flowchart illustrating flows along the product system that are captured by the reviewed CE indicators (black) and flows currently not captured (red). Abbreviations previously not mentioned: Maint, maintenance; RP, repurposing.

3.1.5. *Energy recovery*

The only indicator that has the strategy *energy recovery* as its main focus is the recoverability rate (Rrecov) (Fig. 2e) (Ardente and Mathieux, 2014). It is expressed as the fraction of a product that is energy recoverable given a certain geographical and temporal context.

3.1.6. *Multi-focus*

Nine indicators were identified as multi-focus indicators that do not make use of data related to product function or lifetime. In general, these indicators account more comprehensively for the product system compared to previous groups. The most common combination of strategies is *reducing losses in production* and *material recycling*. For instance, the circular process feedstock intensity (CPFI) and circular process waste factor (CPWF) (Lokesh et al., 2020) are extensions of the FI and WF, respectively, but where the mass of recycled resources recovered at end-of-life is also included. Other combinations are discernible. For instance, the C2C (Fig. 2f) addresses *material recycling* by including the fraction that is potentially recyclable at end-of-life, while also promoting *changing material composition* by rewarding increased recycled content and inclusion of renewable, biodegradable, and compostable materials in a product.

3.1.7. *Multi-focus with function/time included*

Six indicators are considering time and/or function data. They were also found to address several strategies. The MCI accounts for the primary resources incorporated in the product, the waste generated after use, the fraction of reused components, and the utility of the product. The utility is presented as a fraction describing the lifetime and/or function of the investigated product in relation to an industry average. Thus, it has a focus on, e.g. *reducing losses in production, using more of technical lifetime,* and *material recycling.* The PCI (Fig. 2g) is an elaboration of the MCI in an effort to overcome identified limitations in the MCI methodology by, e.g. including production losses and accounting for material and component exchanges with other product systems. Both indicators consider all lifecycle phases apart from extraction since the departure of their analysis is the material production phase, without accounting for raw material input or losses further upstream. Only one of the indicators covers aspects of all lifecycle phases: the relative net loss (RNL) (Ljunggren Söderman and André, 2019). It is derived from the share of materials not functionally recycled, the function, and the service lifetime of a product—including losses occurring in extraction, material production, manufacturing, and recycling. By capturing changes in service lifetime and function it is able to reward improvements related to these aspects, e.g. lifetime extensions or use intensity.

3.1.8. *Existing gaps in resource-based indicators*

To illustrate existing gaps and to highlight areas that currently receive limited attention by the selected indicators, the generic flowchart was extended with flows and processes outlined in Böckin et al. (2020) not addressed by any of the selected CE indicators (Fig. 3). These are primarily resource flows related to lifetime extension strategies like maintenance and product repurposing. Remanufacturing is only accounted for in terms of the component fraction that can be reused in a remanufacturing process, but aspects like additional resource flows or waste flows associated with these operations are not accounted for by any reviewed indicator. Furthermore, there are no indicators that quantify material auxiliaries or energy during the use phase, which means these aspects will remain undetected when using indicators. The extended flowchart illustrates many gaps but is not an exhaustive illustration. For instance, an increased level of detail of the product system would potentially reveal additional unaccounted flows.

3.2. *Testing of indicators*

Not all indicators selected from the review could be applied on the case studies. The specific energy and resource indicator (SERI) (Winzer et al., 2017) is specific to lighting systems and hardly translatable to other types of products. For the emergy-based indicators from Marvuglia et al. (2018) and the PMC, the necessary data were not available in the case studies. The remaining 31 indicators were applied on each case (Fig. 4).

3.2.1. *Explanation of the CE indicators' results per case*

The results from the 31 indicators are briefly explained in Table 3. Further explanations are available in the Supplementary information, section S.7.

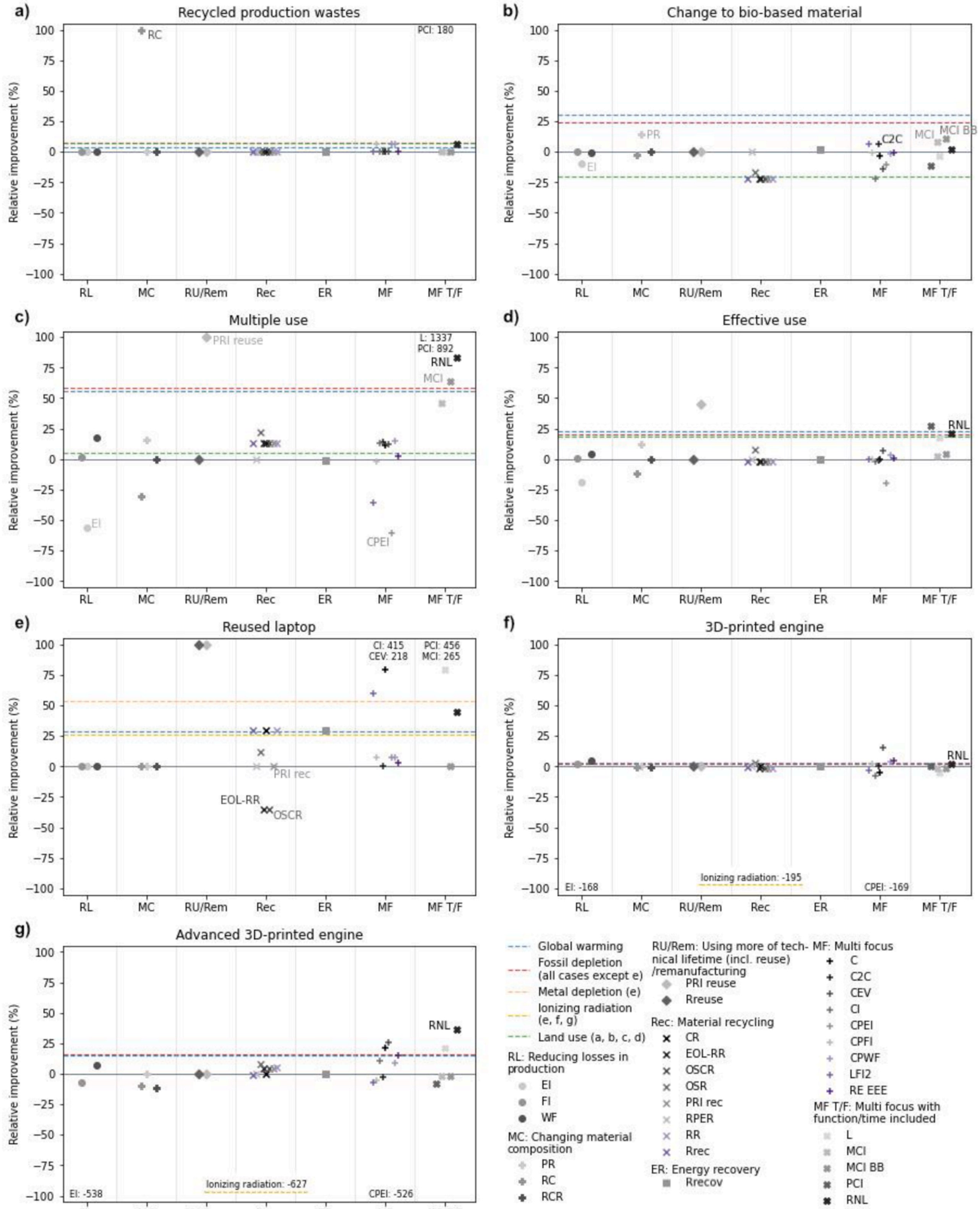

Fig. 4. Relative improvement obtained with the 31 indicators tested and with the selected life cycle environmental impact categories. To facilitate interpretation of the results, the indicators are grouped according to their CE strategy in focus. The indicators specifically mentioned in the text are highlighted with their name on the figure.

Table 3
Explanation of the results from CE indicators in Fig. 4 for each case.

Case	Explanation of CE indicators' results
a	Pre-consumer recycling is either not accounted by indicators (no relative improvement) or positively valued as contributing to less losses from the system (multi-focus indicators with positive values) or more recycled content from pre-consumer recycling (RC indicator).
b	The increased share of bio-based content leads to positive values for the PR indicator and some multi-focus indicators (e.g., C2C, MCI, MCI BB). The negative value from EI indicates that the production is more energy intensive. The negative values from indicators in groups Rec, MF and MF T/M are explained by a lighter packaging, which is the only component sent to recycling. More of the product is incinerated, indicated by positive values from the ER group.
c	The ratio of reused material increases (PRI-reuse), although it is not commercial reuse (null value from Rreuse). Positive values in the MF T/M indicator group highlight the extended lifetime of the product. The production is more energy intensive (EI and CPEI) but generates less waste (WF) and so less recycled content from pre-consumer recycling (RC). The positive values from indicators in groups MC, Rec and MF are explained by the heavier packaging, which is the only component sent to recycling.
d	The lower material requirement for the same function is emphasised by the positive value of the RNL indicators. Indicators from the RL group indicate that the production is more energy intensive (EI) but generates less waste (WF). Indicators from the MC group inform on a lower recycled content from pre-consumer recycling (RC) and on an increased bio-based content (PR). More products are reused (PRI-reuse) after customisation to users' need.
e	The reuse of the laptop results in positive value from the RU/Rem and MF T/M groups due to a higher rate of reused products and an extended lifetime, respectively. More laptops are also sent to proper end-of-life treatment, i.e. both recycling and energy recovery, emphasised by positive values from indicators in the Rec, ER and MF groups. Negative values in the Rec group occur when reusing material is considered to limit the amount of material sent to recycling. The manufacturing of the laptop is not changed, as indicated by null values in the RL and MC groups.
f	3D-printing is energy intensive (EI) but generates less waste (WF). The changed material content of the engine leads to a slight decrease in recycled content (MC group) and to lower recovery rate of metals (Rec group, negative values in MF group). The engine weight reduction is not visible from any MF T/M indicator, probably due to the drawbacks related to recycled content and recovery rates.
g	The 3D-printing with advanced technology is energy intensive (EI) and generates less waste (WF). It allows a different material composition as in case f, with less recycled content (MC group) but higher recovery rates for metal recycling (Rec group and positive values in the MF group). The latter improvement combined with the engine weight reduction explain the positive value of the RNL indicator.

3.2.2. *General observations from the testing of indicators*

The results of changing from BAU to further CE strategies differ between indicators, also within the same group of indicators. Some even have conflicting results. It is clearly seen with indicators focusing on *material recycling* in the reused laptop case (Fig. 4e, group Rec). The commercial reuse activity increases the share of laptops collected for recycling. Most indicators focusing on *material recycling* result in positive values. However, PRI-rec does not indicate any change as it considers the potentially recyclable content and not real collection rates, and the EOL-RR and OSCR indicators display negative values due to a higher quantity of material collected for reuse and not for recycling. Another example is for indicators focusing on *changing material composition* for the incontinence product cases (Fig. 4a-d). The difference in recycled content values is due to the RC indicator accounting for internal recycling, while the RCR indicator does not. For indicators focusing on *using more of technical lifetime* in the multiple use of incontinence products (Fig. 4c), the increased fraction of reused product is only captured by the PRI-reuse. In contrast, the Rreuse only accounts for commercial reuse and as a result there is no improvement of its value.

Some indicator results validate the main improvements sought by implementing further CE strategies. However, these indicators differ between cases. For instance, the reuse of the pants in the case of multiple use of incontinence products (Fig. 4c) is captured by the PRI-reuse underlining the increased fraction of reused material, by the longevity indicator underlining the higher useful lifespan of materials, and by the RNL, MCI and PCI, underlining the lower use and generation of unrecovered materials per use. For the case of more bio-based material (Fig. 4b), the change in material composition is highlighted by the PR outlining a greater renewable content, and by some multi-focus indicators (C2C, MCI and MCI-BB) outlining a reduction of primary material in the product.

Table 4
Explanation of the LCA results on Fig. 4 for each case.

Case	Explanation of LCA results
a	There is an improvement in all impact categories because less material input is required in manufacturing thanks to the internal recycling of production waste.
b	The use of more bio-based material impacts global warming and fossil depletion positively because it replaces fossil-based materials but impacts land use negatively as larger areas are required to cultivate bio-based material.
c	The reuse of pants, assumed to be done to achieve 20 uses, leads to a reduction of material quantity required to provide the same function, visible in the improvement of all impact categories. The impact from washing and drying is found to be negligible.
d	The reduction of material quantity to provide the same function, achieved by effective use of incontinence products, leads to an improvement in all impact categories.
e	There is an improvement of all impact categories, both thanks to more laptops being sent to recycling, and thanks to the use extension and thus a lower material requirement to provide the same product function.
f g	There is an improvement of global warming and fossil depletion due to reduced fuel consumption in the use phase through light-weighting of the truck. The higher impact for ionizing radiation is due to the energy intensive 3D-printing process using Swedish average electricity with a large share of nuclear power. Greater positive and negative values are displayed in case g, due to a further light-weighting and more energy intensive 3D-printing during production.

On the other hand, some of the indicators result in negative values thus pointing to trade-offs between different parts of the system. For instance, the more energy intensive manufacturing process of the multiple use incontinence products (Fig. 4c) is highlighted by the EI. For the case of more bio-based material, less of the product is recycled at end-of-life (Fig. 4b, group Rec). Indeed, as for all incontinence product cases, the changed relative weight of the packaging box, the only part recycled at end-of-life, influences the recycling rates and collection for recycling rates, as a heavier packaging increases the quantity of material recycled. However, the absolute difference in packaging weight is not visible from the results.

3.3. *Comparison to LCA results*

The outcome of the selected environmental impact categories is displayed in Figure 44. A brief explanation of the LCA results per case is provided in Table 4. More detailed information on LCA results is available in the original studies (André et al., 2019; Böckin and Tillman, 2019; Willskytt and Tillman, 2019).

In some cases, the range of values provided by the CE indicators is significantly different from the one offered by the selected environmental impact categories. For instance, the positive values of changing to multiple use of incontinence products and to reuse of laptops (Fig. 4c and e) are more pronounced for some of the indicator results. Furthermore, some consequences are only highlighted by environmental impacts. For instance, the use of more bio-based materials in incontinence products leads to a negative value for land use as more cultivated area is needed to produce bio-based content. For both 3D-printed engine cases, the higher impact for ionizing radiation is due to the use of Swedish average electricity with a large share of nuclear power for the energy intensive 3D-printing process (Böckin and Tillman, 2019). In contrast, the positive value for fossil depletion is due to the low share of fossil energy in the electricity mix combined with the reduction of fuel consumption in the use phase.

4. Discussion

4.1. Circular economy indicators are different

The indicators show a significant divergence in terms of the CE strategies they have in focus and the flows and processes they capture. A majority of the indicators are *single-focus* indicators, i.e. with one strategy in focus, but a significant number are *multi-focus* indicators, which means they consider several CE strategies simultaneously. The two most common CE strategies accounted for by the indicators are *material recycling*, which is the single focus of 11 indicators and is also addressed by all multi-focus indicators, and *reduction of production losses*. The emphasis on recycling conforms both with studies of the current state of CE implementation and previous indicator reviews for the CE, which have highlighted a dominant focus on recycling (Ghisellini et al., 2016; Kristensen and Mosgaard, 2020).

The difference between what the indicators quantify, and as a result, what can be learnt from them, can be seen from the results of the testing. Overall, the relative change varies considerably and in some instances indicators within the same single-focus groups show opposite trends, as explained in 3.2.2..

While the differences between how some product-level CE indicators measure the CE and the different strategies they address have been highlighted in previous reviews (Elia et al., 2017; Kristensen and Mosgaard, 2020), the flowchart mapping explicitly points to the specific parts of the product system that the indicators quantify. A majority of the indicators account for resource flows from only one or two lifecycle phases. In general, the single-focus indicators capture fewer resource flows and a smaller part of the product system, while the multi-focus indicators account for the product system more comprehensively. For instance, most *material recycling* indicators only target the end-of-life phase, while the multi-focus indicators address several phases of the lifecycle. This means that many indicators either 1) only look at a limited part of the product system and thus miss changes occurring outside their scope, or 2) can capture changes that occur but where interpretations of the results are difficult because the indicator is not sufficiently granular. For instance, in the 3D-printed engine cases (cases f and g), the mass of both pre-treatment losses and losses during recycling changes. It is then not possible to determine which parts of the recycling processes that affect the value of the indicators that quantify the finally recycled material, such as the EOL-RR. Consequently, it is important to ensure that sufficient parts of the product system are covered by the indicator used and, if needed, to use multiple indicators that complement each other.

4.2. Indicator limitations

4.2.1. Energy and auxiliary materials

Several indicators account for energy in production (e.g. EI and CEV), the energy recovered at end-of-life (e.g. Rrecov), or the use of production auxiliaries (PMC). However, no indicator accounts for energy or auxiliary material use in the use phase. This aspect plays a substantial role in the LCA results for the 3D-printed engine cases (Table 4, cases f and g). Using only the reviewed indicators, it is therefore particularly difficult to make informed decisions about the resource performance of products in which auxiliary materials or energy in the use phase make up a substantial part of the resource use over the life cycle. This is often the case for durable and active products (Böckin et al., 2020) such as washing machines that use energy, water, and detergents in the use phase (Wasserbaur et al., 2020). For the 3D-printed truck engine cases, fuel consumption results in the largest contributions to a number of environmental impact categories, as shown from the LCA results (Böckin and Tillman, 2019), but which cannot be seen in the results of the indicators. Therefore, auxiliary materials and energy should be considered in CE assessments to accurately reflect the overall resource performance, especially for durable and active products.

4.2.2. Lifetime extension strategies

Some CE strategies related to product lifetime extensions are not included in any of the indicators. Maintenance is not accounted for and as a result the resource use of products expected to require considerable maintenance over the life cycle is not well represented. This could be particularly relevant for durable products with longer lifespans that require regular component replacement to reach their expected lifetime (Kaddoura et al., 2019). Repurposing, meaning the reuse of a product in a new function, is also not accounted for by any indicator. Since repurposing has been identified as promising for reducing resource use (Shirvanimoghaddam et al., 2020), it will be an important CE strategy to consider when new indicators are developed or existing methodologies elaborated on.

4.2.3. Multiple use-cycle system boundary

The choice of system boundary is sometimes limited to only one use-cycle of the product. In the second-hand laptop case, the complete product system contains two cycles: the first for production and first use of the laptop, and the second for preparation for reuse and second use of the laptop. Seven of the tested indicators (MCI, MCI-BB, PCI, CEV, LFI2, PRI-rec and PRI-reuse) focus on activities in the scope of one producing company and thus on the reuse activity and the second use-cycle only. The system boundaries were then limited to the second use-cycle of the laptop life cycle for the assessment of those indicators, excluding production processes and material flows for the original production as well as products unfit for reuse. The development of products that are designed for several use-cycles is particularly important for extending resource use in a circular economy (Campbell-Johnston et al., 2020). Therefore, the possibility for accounting all activities involved in the establishment of such complex circular product systems will be essential for further development of indicators.

4.2.4. Consideration of the functional unit and absolute mass variations

CE indicator results are mainly expressed for one product, disregarding attributes related to the product's provided function or lifetime. Furthermore, since many indicators are calculated from fractions between intermediary flows within the product system, they cannot capture reductions in material use in a product. For both the effective use of incontinence products and the 3D-printed engine, the total product mass is reduced while providing the same function. This improvement is only visible from the RNL, which expresses material flows relative to the function of the product, expressed as a usage provided for a given lifetime. The MCI, MCI-BB, and PCI account for product function by benchmarking the lifetime and intensity of use to an industry average. However, these latter indicators are not able to detect absolute reductions of product mass. This is because the starting point of their calculation is the mass of the product and the other variables, e.g. waste rates, are derived from this through various fractions. All else unchanged, product mass reductions will then lead to proportional reductions in the other parameters and to the end-value being the same. As a result, when using CE indicators, it is important to be aware of whether absolute reductions of resource use are visible from the results and to account for them if this is not the case.

Expressing an impact per unit of product function is a foundational feature in LCA. This enables a comparison of various products based on their provided function, which stands in contrast to all CE indicators in which results are expressed per product, except the RNL. This partly explains why conclusions from CE indicators are not necessarily aligned with those of LCA. One example is the case of packaging boxes for incontinence products with high rates of renewable materials and high recycling rates, relative to the rest of the product. More packaging to provide the same function then leads to better performance for indicators that reward renewable material content and recycling at end-of-life (Fig. 4a-d). It is questionable if using more materials for a given function should be rewarded, and this is clearly corroborated by the LCA results for which global warming, resource depletion and land use impacts increase. This points to the importance of considering the product function as a basis for comparison in the assessment of resource-related effects from CE strategies.

4.3. Indicator selection and development

4.3.1. Flowchart tool

The mapping and testing of CE indicators have highlighted the differences between them and shown that the choice of indicator can have significant effects on the conclusions. Hence a thorough understanding of what indicators actually quantify is critical. By clearly showing the flows and processes captured in the product system, the flowcharts make the indicators easier to apply and facilitate an accurate interpretation of the results. Additionally, since most indicators only address parts of the product system, there is a risk that potential trade-offs between life cycle phases are not adequately captured. Both the identified groups and the flowcharts could be used to guide the selection of a set of complementary indicators that would capture sufficient parts of the system. Lastly, by explicitly pointing to the flows and processes currently not accounted for, the extended flowchart (Fig. 3) can guide the development of new product-level CE indicators or inform elaborations on existing methodologies, e.g. to cover additional parts of the product system or to overcome identified limitations.

4.3.2. Multi- and single-focus indicators

Two main options are relevant for capturing changes in the product system based on the existing range of CE indicators: the use of multi-focus indicators or the use of sets of single-focus indicators.

Multi-focus and comprehensive indicators combine various aspects into one value. Based on the indicator analysis in this study, the MCI, PCI, SERI and RNL are the most comprehensive in terms of the inclusion of product lifetime, function and the number of life cycle phases addressed. Using one of these indicators, there is less risk of missing important resource flow changes in the product system. Besides, an evaluation of one unique value is more straightforward. However, the indicator analysis presented here and previous reviews (Helander et al., 2019; Kristensen and Mosgaard, 2020; Saidani et al., 2019) agree that a single indicator combining all aspects of the CE concept is still missing, which means that no multi-focus indicator currently addresses the entire CE concept. Furthermore, the results of multi-focus indicators are sometimes difficult to interpret. When expected benefits from CE strategies are offset by other consequences, they are difficult to identify through one aggregated value. For the 3D-printing case, both the mass and material content of the product is changed, which leads to multiple desirable and undesirable variations in the share of recycled content, recycling rate and production efficiencies. It is then difficult to explain which changes play a greater role in the final negative outcome of, for instance, the PCI and MCI. Finally, there is an inherent tension between applying a more wide-ranging indicator and the more extensive data this would require.

Single-focus indicators are easier to interpret. An assessment made with several of these indicators provides a more detailed understanding of the consequences of changes in the product system and trade-offs are more clearly outlined. Unlike multi-focus indicators, single-focus indicators inherently do not cover a large range of life cycle phases and flows. Consequently, a set of several complementary single-focus indicators could be selected using the indicator grouping, and the flowchart tool. As an example, one indicator per focus group could provide a starting set, which could then be further supplemented to cover as many CE strategies as deemed necessary.

4.3.3. Recommendations

The limitations identified emphasise the importance of knowing what is left out of the assessment and imply that indicators should be selected with care. Based on this we suggest general recommendations for selecting indicators, which also point to opportunities for elaborating on existing methodologies or developing new indicators.

- The focus of the indicators in the selection should be comprehensive enough to cover the implemented CE strategies and should ensure that the product system is sufficiently covered. This is especially important to consider for combinations of multiple strategies. Furthermore, the selection should be adapted to the case and intended use of indicators. As a result of this, one generic indicator selection cannot be recommended.
- Multi-focus and more comprehensive indicators have a larger coverage of the product system and are aggregated into a single value. For a more detailed understanding of the product system, sets of single-focus indicators are better suited.
- Ensure that multiple use-cycles are covered in their entirety, in contrast to only one use-cycle at a time.
- Account for auxiliary material resources during use, especially for assessments of durable and active products (none of the reviewed indicators capture this).
- Account for maintenance and repurposing processes, especially for durable products requiring frequent component replacement (none of the reviewed indicators capture this).
- Ensure that changes in total mass and service lifetime are visible from the results of the analysis. Having the product function as the basis for the assessment provides the means for capturing these changes.
- The flowchart tool and grouping could be used as guidance for the selection and development of indicators.

As an example of a set of indicators: for the case of multiple use of an incontinence product, it would be of particular interest to use an indicator from the *reducing production losses* group to gain insights on how the production changes with the new design, one *reuse* indicator, and one multi-focus indicator that considers time and function to capture how the shift to multiple use affects the reusability and lifetime of the product.

To complement indicators focusing on material resources, indicators that account for energy use along the product system can be considered, especially where energy use is identified as important. This concerns for example energy in manufacturing (indicators exist) and energy during use (indicators do not exist). For instance, capturing the energy use along the product system is crucial in the 3D printing cases since a shift in energy use can be seen, from the use to the manufacturing phase.

4.4. CE indicators and LCA

In comparison to LCA, most CE indicators provide a time-efficient measure of the resource flows affected when introducing CE strategies for a product. Nevertheless, the type of conclusions from the selected CE indicators is different from those from the LCA results. Indicators capture changes in materials and in some cases also energy resource flows, whereas LCA provides environmental impacts thereof. For instance, the absolute mass reduction of the 3D-printing cases leads to a reduction of fossil energy required during use, which reduces global warming and fossil depletion impacts. In contrast, most CE indicators emphasise the lower recycled content and recovery rate of the engine (Fig. 4f) due to changes in the material content, or the increased energy use in manufacturing. In addition, unlike CE indicators, LCA can point to trade-offs between different impact categories emerging from changes in resource use. As an example, there is a significant trade-off in the LCA results between climate change impacts and ionizing radiation for the 3D-printing cases, a result of lower fossil energy consumption during use at the cost of increased energy consumption from nuclear sources during production. In contrast, indicators quantifying energy do not capture changes relating to energy in the use phase nor distinguish between different types of energy and their associated emissions.

Another explanation for the difference in the results from indicators and LCA is the distinction between different types of materials included in the resource flows. No indicators make a distinction between resources in terms of scarcity, criticality, or toxicity, but some indicators distinguish between renewable and non-renewable resources (Table 2). While previous authors, such as Elia et al. (2017) and Corona et al. (2019), have argued that CE indicators should reward the inclusion of renewables or disincentivize the use of scarce resources, we posit that resource-based indicators should make no direct prioritization between different types of resources. This is because the use of, e.g. renewable resources within a product system does not guarantee preferable environmental outcomes, as shown by the negative result for land use in the case of bio-based incontinence products (Fig. 4b). In contrast, the wide scope of environmental impacts of materials is central to methods such as LCA. The knowledge of resource use provided by resource-based CE indicators cannot substitute environmental assessments performed with LCA. Therefore, complementing CE indicators with LCA should be considered when information on environmental impacts is sought.

5. Conclusions

This study has reviewed existing product-level resource-based CE indicators, presented a detailed flowchart tool that illustrates the flows and processes the indicators quantify, tested them on seven real cases, and compared the indicator results with those from environmental assessments done with LCA.

The flowchart mapping shows that indicators vary significantly in terms of their focus and the parts of the product system they account for. When tested on the seven cases, the relative change of the indicators varied considerably, at times even when having the same CE strategy in focus. This is because the indicators quantify distinctly different flows in the product system, and most only capture a limited part of the system. This indicates that a specific set of indicators cannot be recommended for all situations and should instead be adapted to the purpose of the assessment. A number of limitations in existing indicators have been identified: auxiliary material or energy during use are not accounted for although it might contribute substantially to overall resource use for active products. Some product-life extension strategies, e.g. maintenance and repurposing, are missing and multiple use-cycles are not possible to assess with 7 out of the 31 tested indicators. Finally, absolute mass variations are only visible in the results of one indicator since mass flows are mostly expressed relative to other flows within the same system.

The flowchart tool and grouping presented here could be used to guide the selection and interpretation of indicators. Moreover, it is important to ensure that sufficient parts of the product system are covered, that changes in total resource use and service lifetime can be seen from the results, and that both material and energy use along the product system are captured. A clearer understanding of the consequences of implementing CE strategies is possible with single-focus indicators, while multi-focus indicators foster a more comprehensive assessment and could provide a more straightforward conclusion. Additionally, opportunities for the further development of indicators have been outlined and an extended flowchart model (Fig. 3) presented, which could serve as guidance for this purpose.

Finally, this study shows that conclusions from CE indicators and LCA are not necessarily aligned. LCA accounts for the differentiation of materials in resource flows and for translating the effects of these flows and their processing into potential environmental impacts, while resource-based indicators only account for the resource flows. When information on environmental aspects is sought, CE indicators should be complemented with environmental assessment tools such as LCA.

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.

Table A.1
List of indicators and their abbreviation used in this article

Symbol	Name
CEV	Circular Economic Value
C	Circularity
CI	Circularity Index
CPEI	Circular-process energy intensity
CPFI	Circular-process feedstock intensity
CPWF	Circular-process waste factor
CR	Collection rate
EOL-RR	End-of-life recycling rate
EI	Energy intensity
FI	Feedstock intensity
LRR	Landfill to recycle ratio
LFI2	Linear flow index for product families
L	Longevity
MCI	Material Circularity Indicator
C2C	Material Reutilization Score
MCI-BB	MCI for bio-based and biodegradable products
OSCR	Old scrap collection rate
OSR	Old scrap ratio
PRI-rec	Potential recycle index
PRI-reuse	Potential reuse index
PMC	Process material circularity
PCI	Product Circularity Indicator
PR	Product renewability
RE EEE	Resource efficiency indicator for electrical and electronic equipment
Rrecov	Recoverability rate
Rrec	Recyclability rate
RBR	Recycle benefit ratio
RYR	Recycle yield ratio
RC	Recycled content
RCR	Recycled content rate
RPER	Recycling process efficiency rate
RR	Recycling rate
RNL	Relative net loss
Rreuse	Reusability rate
SERI	Specific Energy and Resource Indicator
WF	Waste factor

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.106080.

Appendix A

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