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Testing product-level indicators for a more circular economy

Adeline Jerome[a], Harald Helander[a], Maria Ljunggren[a], Matty Janssen[a]
a) Chalmers University of Technology, Gothenburg, Sweden

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Abstract: Product level indicators can be essential for companies to guide and monitor the transition towards a more circular economy (CE). In particular, CE indicators focusing on physical resource flows are needed for informing businesses on the environmental performance of their product portfolio. Many of those indicators have been suggested but a robust assessment framework has yet to be developed. Previous reviews highlighted the limited range of CE strategies covered by one indicator at a time and recommended the use of a set of indicators to ensure comprehensive assessments. Furthermore, many existing indicators have only been tested individually on few and simple products. The aim of this study is to examine the extent to which existing product-level circularity indicators are applicable to real case studies with different combinations of CE strategies. Starting from a review of the literature to identify resource-flow based indicators suitable for product-level assessment, 36 indicators are applied to three real case studies. Challenges linked to a high level of detail in product systems implementing CE strategies were encountered when applying communicated methodologies and analysing the quantitative results from the 31 indicators that were successfully applied. This paper suggests selecting both comprehensive indicators and a range of single-focus indicators to ensure an understanding of the systemic consequences of implementing CE strategies. The results also demonstrate the importance of a clear understanding of what is measured and what is missed by a given selection of CE indicators for informed decision-making.

Introduction

Indicators can be essential tools to guide and monitor the transition towards a more circular economy (CE), and are being developed at supra-national (European Commission, 2018), national (Geng et al., 2012), company and product levels (Saidani et al., 2019). For companies, a set of product-level CE indicators could be used for 1) internal purposes, such as monitoring progress or assessing potential changes to product portfolios, and for 2) external purposes, such as benchmarking with other companies and communicating with customers and suppliers. Good indicators are consistent, time-efficient and communicative measures that clearly reflect the objectives targeted for the transition. One such target is improving the environmental impact of products and services (Kirchherr et al., 2017). When studying the environmental impact of a product, physical resource flows that are part of the product system, either as input or output flows, or as internal flows, are taken as a starting point. Product-level indicators focusing on physical resource flows are therefore needed for informing businesses on the environmental performance of their product portfolio.

Previous reviews of CE indicators agree on the necessity of combining existing indicators as they individually are too limited to sufficiently cover the range of potential CE strategies (Corona et al., 2019; Helander et al., 2019; Kristensen & Mosgaard, 2020). Furthermore, many existing indicators are only tested on few and often simple products. Testing indicators has however been recognized as an effective way to identify strengths and weaknesses in measurement frameworks for gradual improvements (Meadows, 1998). Only a few studies have used available indicators on cases for another purpose than exemplifying a newly developed indicator (Lonca et al., 2018; Niero & Kalbar, 2019; Saidani et al., 2017; Walker et al., 2018). Only two or three CE indicators are then simultaneously applied to be compared to other assessment frameworks.

This study aims to examine the extent to which existing product-level and physical resource-flow based circularity indicators are applicable to case studies with different combinations of CE strategies. Both the challenges hindering the feasibility of consistent application of existing indicator methodologies and the conclusions provided by their quantitative results are analysed to formulate recommendations for selecting and developing CE indicators. To this end, existing relevant indicators are identified and applied on three real case studies.

Method

Identification of CE indicators

The identification of existing CE indicators in scientific and grey literature based on physical resource flows was performed with a systematic review in August 2020. 36 indicators were selected with a procedure detailed in (Harald Helander et al., 2021). All indicators were deemed applicable to assess products, excluding indicators with a wider scope such as companies.

Using the framework from Böckin et al. (2020), the CE strategies in focus in the definition of each CE indicator were identified. The distinction between indicators focusing on one or multiple CE strategies emerged from this analysis (Table 1). Additionally, indicators requiring product lifetime and/or function were identified to be multi-focused and are further distinguished from multi-focused indicators without time or function consideration. Single-focus indicators were also further distinguished based on the CE strategy in focus.

CE strategy in focus	Symbol	Name	Reference
Reduce losses in production	EI	Energy intensity	(Lokesh et al., 2020)
	FI	Feedstock intensity	(Lokesh et al., 2020)
	PMC	Process material circularity	(Lokesh et al., 2020)
	WF	Waste factor	(Lokesh et al., 2020)
Change material composition	PR	Product renewability	(Lokesh et al., 2020)
	RC	Recycled content	(Graedel et al., 2011)
	RCR	Recycled content rate	(Ardente & Mathieux, 2014)
Use more of technical lifetime (incl. reuse)	PRI reuse	Potential reuse index	(Mesa et al., 2018)
	Rreuse	Reusability rate	(Ardente & Mathieux, 2014)
Recycle material	CR	Collection rate	(Haupt et al., 2017)
	EOL-RR	End-of-life recycling rate	(Graedel et al., 2011)
	LRR	Landfill to recycle ratio	(Marvuglia et al., 2018)
	OSCR	Old scrap collection rate	(Graedel et al., 2011)
	OSR	Old scrap ratio	(Graedel et al., 2011)
	PRI rec	Potential recycle index	(Mesa et al., 2018)
	RBR	Recycle benefit ratio	(Marvuglia et al., 2018)
	RPER	Recycling process efficiency rate	(Graedel et al., 2011)
	RR	Recycling rate	(Haupt et al., 2017)
	Rrec	Recyclability rate	(Ardente & Mathieux, 2014)
	RYR	Recycle yield ratio	(Marvuglia et al., 2018)
Recover energy	Rrecov	Recoverability rate	(Ardente & Mathieux, 2014)
Multiple focus	C	Circularity	(Figge et al., 2018)
	C2C	Material Reutilization Score	(C2CPII, 2016)
	CEV	Circular Economic Value	(Fogarassy et al., 2017)
	CI	Circularity Index	(Cullen, 2017)
	CPEI	Circular-process energy intensity	(Lokesh et al., 2020)
	CPFI	Circular-process feedstock intensity	(Lokesh et al., 2020)
	CPWF	Circular-process waste factor	(Lokesh et al., 2020)
	LFI2	Linear flow index for product families	(Mesa et al., 2018)
	RE EEE	Resource efficiency indicator for electrical and electronic equipment	(Juntao & Mishima, 2017)
Multiple focus with function and/or time included	L	Longevity	(Figge et al., 2018)
	MCI	Material Circularity Indicator	(Ellen MacArthur Foundation & ANSYS Granta, 2019)
	MCI BB	MCI for bio-based and biodegradable products	(Razza et al., 2020)
	PCI	Product Circularity Indicator	(Bracquené et al., 2020)
	RNL	Relative net loss	(Ljunggren Söderman & André, 2019)
	SERI	Specific Energy and Resource Indicator	(Winzer et al., 2017)

Table 1. List of indicators identified.

Testing on real cases

The indicators are tested on the three following studies: 1) more effective use of incontinence products through recycling of production waste, partial reuse, increased share of renewable materials and customisation to user's needs (Willskytt & Tillman, 2019), 2) reuse of laptops (André et al., 2019), and 3) weight reduction of a truck engine through 3D-printing (Böckin & Tillman, 2019). For each case included in those studies, the implementation of new CE strategies is compared to a business-as-usual (BAU) case, representing the current implementation of CE strategies, e.g. recycling. Each case is described in Table 2 and more details are available in the respective publications. Their modelling was based on collaboration with the respective companies involved which encompasses the complexity of CE implementation in contrast to theoretical cases.

Study	Case	Main strategy	Description
Incontinence products	Recycled production wastes	Recover energy	All production wastes to incineration. As for all strategies for incontinence products, the packaging box is recycled, and the product incinerated after end-of-life
		Reduce losses in production; Recycling	All production wastes are recycled back to production
	Change to bio-based material	Recover energy; Recycling	Absorption pad with 63% renewable material
		Change material in product; Recover energy; Recycling	Absorption pad with 73% renewable material
	Multiple use	Recover energy; Recycling	All-in-one product discarded after use
		Shift to multiple use; Recover energy; Recycling	Absorption pad discarded after use, pants washed and reused 20 times before being discarded
	Effective use	Recover energy; Recycling	Choice of products according to user preference
		Use effectively; Recover energy; Recycling	Choice of products after urinary leakage measurement, leading to an average of 20% of material reduction to provide the same function
Laptop	Reused laptop	Recycling	Laptop discarded after 3 years, 50% are collected for recycling
		Use more of technical lifetime (reuse); Recycling	All 3-year-old laptops are collected. 70% are reused for 3 more years, 30% are sent to recycling. After second use, 50% are collected for recycling
Truck engine	3D-printing	Recycling	Conventional engine of 533 kg. As for all strategies related to the truck engine, the engine is shredded after use and major recyclable metal fractions are sorted and recycled. Recovery rate of 100% for low-alloy steel, 90% for cast iron, 87% for stainless steel.
		Reduce use of auxiliary materials and energy; Reduce material quantity in product; Change material in product	Engine of 499 kg. 20% of the engine is 3D-printed, with aluminium when replacing aluminium parts and with stainless steel when replacing cast iron and low-alloy steel
	3D-printing advanced technology	Recycling	Conventional engine of 533 kg.
		Reduce use of auxiliary materials and energy; Reduce material quantity in product; Change material in product	80% of the engine is 3D-printed, leading to a weight of 418 kg. Aluminium when replacing aluminium parts and low-alloy steel when replacing cast iron and low-alloy steel.

Table 2. Description of cases with BAU cases highlighted in grey.

The selection covers a range of product types. Incontinence products are consumable and disposable products while laptops and truck engines are more durable products. The CE strategies applied in each case (see Table 2) are representative of the four groups of strategies highlighted by Böckin et al. (2020): extraction and production, use effectively and efficiently, extend use and post use.

For each CE case and BAU case, the 36 selected CE indicators are applied based on their published methodology in order to detect challenges in their application. The relative improvement RI is then calculated for each indicator and case as follow:

$$RI = \alpha \frac{CE\ case\ result - BAU\ case\ result}{CE\ case\ result}$$

with α taking the value of 1 if higher values of this indicator are desirable or -1 if lower values are desirable. The relative improvements are used to compare CE indicators based on the conclusions they provide.

Results and discussion

Application of indicators

Out of the 36 indicators identified, five were not possible to apply in this study. The Specific Energy and Resource Indicator (Winzer et al., 2017) is too specific to lighting systems to be translated to other product types. The distinction between auxiliaries and other inputs for all pre-consumer processes necessary for the process material circularity indicator (Lokesh et al., 2020) and emergy data for the indicators from Marvuglia et al. (2018) were not available within the scope of this study.

The remaining 31 indicators were successfully assessed, but the available methodology sometimes had to be supplemented with assumptions to be applicable to the studied cases. A first reason was the lack of application examples provided for two indicators, the Circular Economic Value (CEV) (Fogarassy et al., 2017) and the Resource efficiency indicator for electrical and electronic equipment (RE EEE) (Juntao & Mishima, 2017). The unclarities from their method description are then not possible to be checked on an example. For instance, the identification of appropriate system boundaries for the CEV or the specific resource flows that should be accounted as “really used in the product” (Juntao & Mishima, 2017) in the RE EEE left too much room for interpretation. A second reason was the higher level of detail of the product systems in the tested cases compared to the theoretical systems described by some indicator methodologies. For instance, seven of the tested indicators (Material Circularity Indicator (MCI) (Ellen MacArthur Foundation & ANSYS Granta, 2019), MCI for bio-based and biodegradable products (MCI BB) (Razza et al., 2020), Product Circularity Indicator (PCI) (Bracquené et al., 2020), CEV, and the three tested indicators from Mesa et al. (2018)) allow only to focus on one use cycle of a product. For the reused laptop case, the system boundary was then chosen to only include the treatment for reuse, the second use and end-of-life recycling of the laptop, but another choice could have been to include collected but non-reusable laptops (0.3 per laptop reused) as wastes from the reuse treatment. The level of detail of the processes involved in real cases also requires high precision in the description of the flows to be included to guarantee reliable assessment, such as the distinction between the resource flow entering or leaving the recycling facility. The inclusion of a system flowchart such as for the PCI or the recycling ratios from Haupt et al. (2017) and Graedel et al. (2011) reduced risks of misinterpretation.

This testing highlighted the need for a better documentation of existing indicators to allow a reliable systematic application of CE indicators. The implementation of CE strategies involves more complex relationships between processes and the combination of CE strategies (Blomsma & Brennan, 2017). Developing indicators to handle the complexity of real cases is important.

Another challenge to the systematic application of the tested CE indicators was the highly demanding data requirements, especially for multi-focus indicators. For instance, efficiencies of all material and component production are expected as input in the PCI. Its assessment requires a comprehensive study of the product system but comes at the expense of time and data intensity and might not be appropriate for early-stage assessment in product design support. There is a trade-off between comprehensiveness and early guidance which requires clear understanding of what is measured and what is not.

CE indicators results

The values from the testing vary greatly from indicator to indicator, even for indicators with the same CE strategy in focus (Figure 1). For instance, the reusability rate (Rreuse) (Ardente & Mathieux, 2014) only accounts for commercial reuse and thus excludes improvement of a shift to multiple use of incontinence products performed by the user unlike the potential reuse index (PRI reuse) (Mesa et al., 2018).

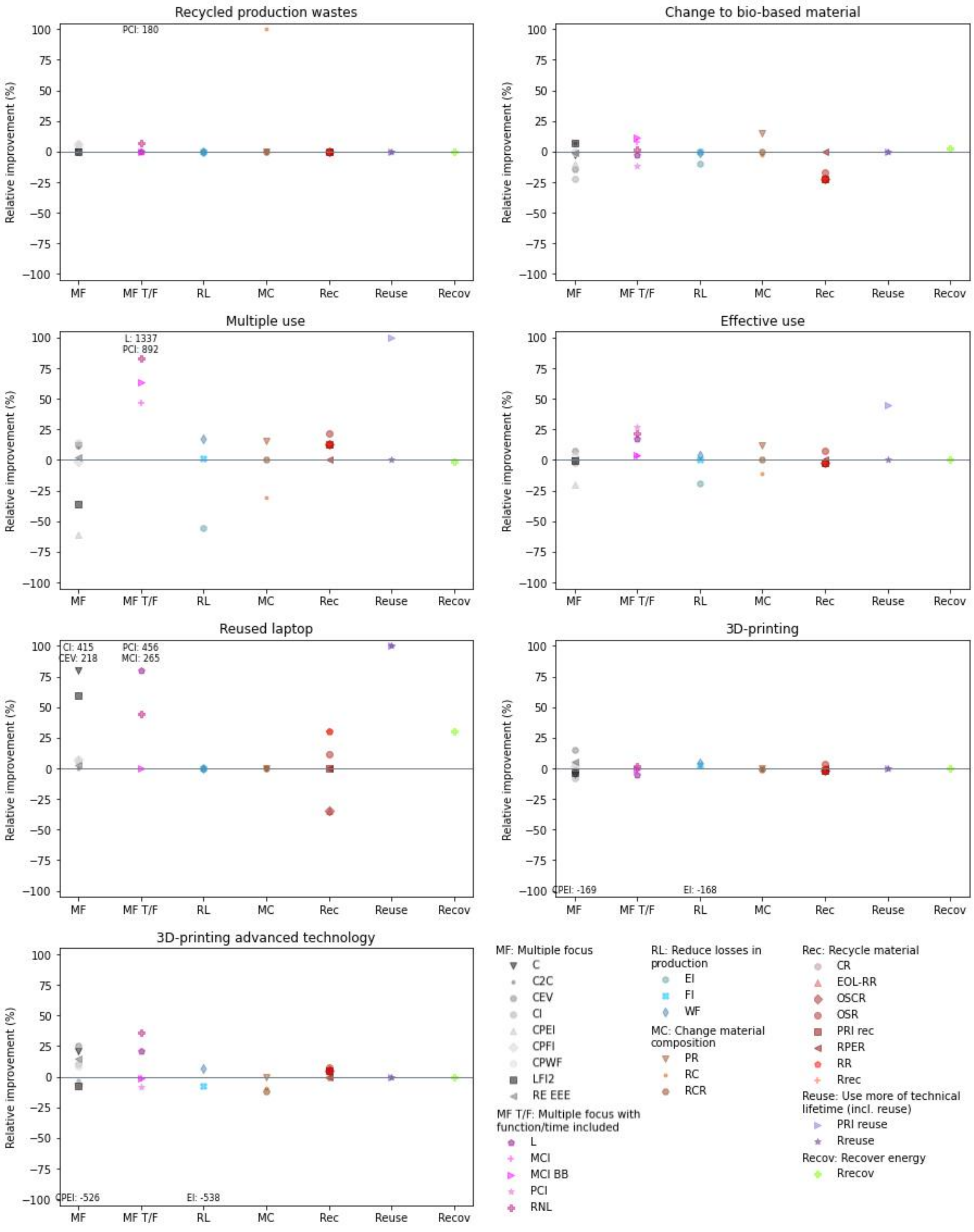

Figure 1. Results for the 31 CE indicators per case.

For some cases, the obtained values confirm the intended improvement of implementing the new CE strategies. For instance, the change to more bio-based content in incontinence products is highlighted by the product renewability (PR) indicator (Lokesh et al., 2020) and material reutilization score (C2C) (C2CPII, 2016). The shift to multiple use of incontinence products and the reuse of laptops are emphasized by both positive values from indicators focusing on reuse and from indicators considering product function and/or lifetime. For those latter, the extended product lifetime through reuse or shift to multiple use is either valued as more used lifetime of resources in the system (longevity indicator (L) (Figge et al., 2018)), as less system losses per functional unit (relative net loss (RNL) (Ljunggren Söderman & André, 2019)), as a better performance compared to an industry average (MCI, MCI BB and PCI for the case of multiple use of incontinence products), or as a reduction of virgin material in the product (MCI and PCI for the reused laptop case).

For other cases, the outcomes from the main CE strategies implemented are more difficult to discern. In the case of recycled production wastes on incontinence products, no improvement for reduced losses in production (RL group in Figure 1) nor for material recycling (Rec group) is highlighted by single-focused indicators. Some multi-focus indicators (PCI, RNL) account for the recycling of production wastes as a reduction of losses from the system, and the recycled content (RC) indicator identifies an increase of recycled content in the product. Overall, the avoidance of production wastes is emphasized, leaving out choices in their treatment from the assessment. For the effective use of incontinence products and both cases of engine 3D-printing, the reduction of material quantity to provide the same function is not clearly apparent in the results. Only the RNL indicator is able to account for the absolute mass reduction per function provided, as material flows are not expressed relatively to other flows in the system. Finally, the reduced auxiliary material consumption during use, i.e. fuel consumption, for the 3D-printed engine is not visible from the results.

Apart from highlighting the main CE strategies implemented, CE indicators also point to other consequences in the system. Energy intensive production processes for 3D-printing and for the reusable part of incontinence products are visible with the energy intensity (EI) and circular-process energy intensity (CPEI) indicators (Lokesh et al., 2020). Consequences on material content and end-of-life scenario from the new designs that are developed as part of CE strategies are underlined. For incontinence products, the variation of packaging weight, the only product part sent to material recycling, impacts recycling rates (Rec group) negatively for the case of bio-based product (lighter packaging) and positively for the case of multiple use (heavier packaging). It also impacts positively the renewable content (PR indicator) for the multiple use case. For the 3D-printed engine, recycling rates (Rec group) are negatively impacted by the higher share of stainless steel, with a lower recovery rate, and positively with low-alloy steel in the case of advanced technology, with a higher recovery rate. Results for the effective use of incontinence products are more difficult to interpret as they result from many combined changes in the products.

Choice of indicators for CE assessment

The testing of CE indicators provides insights for recommending a selection of indicators. The different consequences on the product system are better understood with single-focus indicators. They can point to specific aspects that are masked by other changes in multi-focused indicator results, which was essential for drawing detailed conclusions on the tested case studies.

However, a comprehensive indicator combining several aspects into one value can give a clear value position in case of diverging results on several aspects, e.g. an improvement of the MCI in the case of the change to bio-based material in incontinence products with a smaller material share sent to recycling at end-of-life. Moreover, they compel to study a larger part of the product system and multiple aspects of the CE unlike indicators with a single focus. Consequently, it seems preferable to build a product assessment on one comprehensive indicator supported by a representative set of single-focus indicators to provide detailed explanations on the conflicting consequences to be addressed in product design.

In the context of a contested concept such as CE, the choice of indicators also shapes the understanding of the concept (Mair et al., 2018). For instance, only one indicator of the two identified as focusing on reuse accounts for the shift to multiple use of incontinence products. It is then important to have a transparent indicator selection based on a good understanding of the systems that have to be assessed (Burgass et al., 2017).

Conclusions

In this study, 31 resource-flow based CE indicators were tested on real cases in order to provide recommendations on the future use and development of indicators. The results highlighted challenges linked to high level of detail of product systems implementing CE strategies. First, methodologies should be adaptable to very different systems. Implementation examples as well as method illustrations on generic system flowcharts were empirically found to ease a reliable application of CE indicators. Then, it becomes necessary to draw conclusions from both multi-focus indicators and a set of single-focus indicators. The latter focuses on only one limited aspect of the product system but refines conclusions from comprehensive indicators by highlighting different consequences that could be addressed in a product's development.

The variability of values obtained for indicators with the same focus demonstrates the importance that the choice of indicators has on the understanding of the CE. With possible limitations in data availability for early phase assessments, a clear understanding of what is measured and missed by a selection of indicators is necessary for informed decision-making. The results presented in this study showed for example the absence of consideration of auxiliary material consumption during use, but detailed information on the consequences on production efficiency and end-of-life scenarios. This study sought to provide empirical knowledge on the applicability of the indicators, and a next step in this direction would be to connect it to more theoretical analysis such as a detailed flowchart mapping of each indicator.

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