Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 105 (2022) 835–840

www.elsevier.com/locate/procedia

29th CIRP Life Cycle Engineering Conference

Usability and Usefulness of Circularity Indicators for Manufacturing Performance Management

Fu-Siang Syu[a], Adarsh Vasudevan[a], Mélanie Despeisse[a]*, Arpita Chari[a], Ebru Turanoglu Bekar[a], Maria M. Gonçalves[b], Marco A. Estrela[b]

[a] *Chalmers University of Technology, Department of Industrial and Materials Science, 41296 Gothenburg, Sweden*
[b] *Low Carbon and Resource efficiency, R&Di, Instituto de Soldadura e Qualidade (ISQ), R. Mirante 258, 4415 - 491 Grijó, Portugal*

* Corresponding author. Tel.: +46 31 772 1000; fax: +46 31 772 3872. *E-mail address:* melanie.despeisse@chalmers.se

Abstract

Advances in industrial digitalization present many opportunities for process and product data exploitation in manufacturing, unlocking new systemic measures of performance beyond a single machine, process, facility area and even beyond the factory gates. However, existing data models and manufacturing systems' performance measures are still focused on productivity, quality and delivery time, which could potentially lead to an accelerated linear economy. To shift to more circular industrial systems, we need to identify and assess circularity opportunities in ways that align the goals of sustainable and industrial development. In this study, micro-level circular indicators were reviewed, selected, analysed and tested in a manufacturing company to evaluate their usability and usefulness to guide process improvements. The aim is to enable circular and eco-efficient solutions towards sustainable production systems. Usability and usefulness of the indicators are essential to their integration into established environmental and operations management systems. The main contribution of this study is in the identification of key features making circularity indicators usable and useful from a manufacturer's perspective. The conclusion also suggests directions for further research on tools and methods to support circular manufacturing.

Keywords: Circular economy; Circularity indicators; Sustainable manufacturing.

1. Introduction

Technological advances associated with the on-going digitalization trend present new opportunities to enhance the performance of complex industrial systems by exploiting the growing pool of process and product data [1]. Examples of digital technologies used in manufacturing include big data, Internet of Things, cloud computing, cyber-physical systems, machine learning and digital twins [2,3]. Such connected systems can unlock new levels of performance with more holistic measures beyond a single machine, process, or facility area, and even beyond the factory gates [4].

However, manufacturing systems' performance measures are still focused on productivity, quality and delivery time, which could potentially lead to an accelerated linear economy (produce more, faster, better). In addition, existing data and data models are not always suitable to support economic, social and environmental sustainability [5]. Research to overcome data quality issues [6] and other challenges is needed to increase the digital maturity in manufacturing [7]. To shift to a more circular economy (CE), we need to identify and assess circular opportunities focusing on waste and end-of-life (EOL) products to align the goals of sustainable and industrial development.

CE still lacks consensus in its definition due to diverging perspectives from the different researchers and practitioners. To remedy this issue, a single comprehensive definition was proposed: *"an economic system that replaces end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production and consumption processes.*

10.1016/j.procir.2022.02.138

It operates at micro, meso and macro levels, with the aim to accomplish sustainable development" [8].

In contrast to previous industrial development which led to natural resource depletion and other environmental issues, CE promotes the shift away from the current linear flow model to a circular model [9] and enhance the environmental, social and economic sustainability of industrial systems. Numerous circularity indicators have been developed and reviewed by different researchers [10-13]. The indicators measure the degree of circularity of a system quantitatively or qualitatively. Kumar et al. [9] emphasised the importance of measuring CE first at a micro-level, then at meso- and macro-levels. Micro-level indicators can support actions to improve the circularity of a product or a company and macro-level indicators can support the implementation of CE at country or region level.

While many micro-level circularity indicators exist, they are rarely used in the manufacturing industry. This paper presents an industrial case study to evaluate the usefulness and usability of circularity indicators from a manufacturer's perspective to promote their adoption as drivers of industrial development.

2. Methods

To evaluate the usability and usefulness of micro-level circularity indicators in the manufacturing industry, various methods were used to combine a literature study and empirical data from a manufacturing company. The case study was conducted in collaboration with a case company: European original equipment manufacturer (OEM) that uses injection moulding to produce food-grade plastic products.

2.1. Literature study

Circularity indicators were collected from the literature using the following keywords search in Scopus: *((circular* W/2 indicator) AND (manufact* OR production))*. In addition, four review papers were used to identify additional papers using snowballing [10-13]. Most of the micro-level circularity indicators collected were developed in recent years; few papers were published before 2015. The development of micro-level circularity indicators has accelerated since the material circularity indicator (MCI) was published [14].

The indicators collected were categorised based on their characteristics. This initial categorisation resulted in 40 micro-level indicators selected for further analysis to evaluate the usability and usefulness of each indicator. Table 1 shows the usability and usefulness criteria based on [5] which were used to evaluate the micro-level indicators. The usability criteria focus on whether the indicators can be calculated (for quantitative indicators) or qualified (for qualitative indicators). The usefulness criteria are largely similar but focus on whether the indicators fulfil a company's needs. For example, some indicators are easy to calculate but may not capture specific aspects a company wants to improve or only points to improvements beyond their area of control; such indicators would have high usability but low usefulness.

Besides the criteria listed in the table, other aspects of usability included the data requirements and assessment methodology for each indicator. Other aspects of usefulness included the level of implementation (unit of analysis), possible applications, and the circular strategies addressed.

Table 1. List of usability and usefulness criteria used to assess the micro-level indicators based on [5] (superscript annotation: ^{1} usability; ^{2} usefulness).

Criterion	Description
Measurability^{1,2}	Can be measured or quantified
Ease of use^1	Without high costs and time-consuming procedures
Ease of understanding^{1,2}	No or little prior knowledge required to calculate and use the indicator
Data availability^1	Data required readily available or prepared easily
Strategic relevance^2	In accordance with the company's mission
Validity^2	Correctly represents the system being assessed
Reliability^2	Gives accurate and consistent values
Transparency^{1,2}	Possibility of third-party verification
Generalisability^2	Interpretation independent of industry and product
Simplicity^{1,2}	Low dimensionality, few indicators or single index
Compatibility^{1,2}	Standardised, compatible with other methods
Information sharing^{1,2}	Non-sensitive information to enable open exchange with stakeholders
Evolvability^{1,2}	Possible to update and meet evolving requirements

2.2. Case study

To complement the literature study with empirical data, an online survey, workshop and waste management scenarios were used to select and test five micro-level circularity indicators at the case company. The online survey included open-ended questions regarding the case company's approach to sustainability as well as multi-choice questions about desirable features of indicators. The survey helped identify the circular strategies of interest to the case company, thus used as a basis for selecting the indicators to be tested. The indicators were further filtered based on data availability and relevance to the manufacturing process being assessed, resulting in a final selection of five indicators tested by applying them to a production line with five waste management scenarios.

A workshop was conducted with the representatives of the case company to evaluate what features of an indicator make it usable and useful (Table 1). The five indicators were presented with their description, application, data requirements, and calculated scores. The workshop participants were invited to express their opinion about each indicator. The empirical results reported in this paper focus on the usability and usefulness criteria highlighted as important by the company.

3. Results

This section presents the usability and usefulness evaluation of the micro-level indicators reviewed (section 3.1) and tested (section 3.2) in this study. We describe the characteristics of the indicators collected from literature review along with the insights collected from the case company. Finally, we present a case study applying five indicators to the company's manufacturing system.

3.1. Evaluating micro-level circularity indicators

A total of 40 micro-level circularity indicators were selected from the literature study [14-53]. The main applications of these indicators can be divided into four implementation levels (Table 2): material, product, process and firm. Most of the indicators aim to support users in taking actions, such as identifying areas of improvement, strategy formulation, alternative choice, feasibility analysis, etc. The indicators also serve as tools for tracking progress, benchmarking, and communication. As the definition of circularity can vary, the interpretation of the circularity performance represented by these indicators should consider the assumptions and context of the original document (see references provided).

Table 2. Implementation levels and applications of circularity indicators.

Level	Application
Material	• Estimate value-based recycling rate of material [15]
	• Assess the circularity of material [16]
	• Estimate the longevity of material in the product system [17]
	• Assess the quality properties of material [18]
Product	• Compare different life cycle scenarios or alternatives [19-24]
	• Compare treatment options of EOL product [25-29]
	• Assess product circularity and resource efficiency [14,30-34]
	• Circular product development and optimization [35-39]
	• Benchmark and communication [40]
Process	• Identify improvement opportunities in manufacturing and remanufacturing processes [41-43]
	• Assess disassembly performance (cost, time, etc.) [44-46]
Firm	• Identify business opportunities, formulate strategies [47-50]
	• Assess the sustainability and circularity of a firm [51,52]
	• Improve the waste management in a firm [53]

The 9R framework for CE covers potential strategies for narrowing, slowing or closing material loops [8]: rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. The 9R circular strategies provide guiding principles to develop policies and practices to improve the circularity of products or companies. The strategies should be prioritised considering a hierarchical order; i.e., pollution prevention takes precedence over pollution control. The selected indicators usually cover multiple circular strategies, mostly focusing on recycling (38 indicators), reuse (31 indicators), and remanufacture (28 indicators). Interestingly, few indicators are able to cover rethink [14;20;21;39;48] and reduce [20;21;38;41;50;51;53], showing that more research is needed on these high-priority strategies, such as servitization and sharing products or improving manufacturing efficiency.

The measurability of the indicators was categorised as quantitative and qualitative indicators, accounting for 93% and 7% of the selected indicators respectively. Although quantitative indicators are dominant, qualitative indicators (e.g., excellent/poor, high/low, avoidable/unavoidable, etc.) can also provide practical information to guide the implementation of circular strategies. For example, three qualitative indicators aim to find circular pathways [47], assess the quality of materials, components and products [18], and assess the degree of material leakage in a product life cycle [49] with qualitative data obtained through questionnaires.

Most of the selected indicators had predefined equations to provide quantitative results. To prepare the input data or parameters required for these equations, various methods or tools are needed as listed in Table 3. Analytic Hierarchy Process (AHP) and Delphi method serve as the methods for deciding weighting factors of different sub-indicators. Life cycle assessment (LCA) is mainly adopted by the indicators which take the whole life cycle of a product or an activity into account. While LCA is a valuable method for estimating environmental impacts, some barriers hinder its application in manufacturing companies, such as time-consuming and costly procedure, lack of inventory data, and prior knowledge required [54]. Life cycle cost analysis (LCCA) estimates the potential economic benefits of adopting new strategies. Some indicators require product or process modelling to acquire information related to different scenarios or design alternatives [40,45]. Multi-criteria decision analysis (MCDA) aims to evaluate new strategies from multiple points of view, e.g., economic, environmental, societal, business, and technical aspects. Some indicators require more than one method, such as the eco-efficiency index combining LCCA and LCA [21].

Table 3. Method or tool used to apply the selected circularity indicators.

Method or tool	Description
AHP	Structured method for decision making, based on mathematics and psychology [37]
Delphi method	Qualitative method of forecasting by collecting opinions from experts [50]
LCA	Method to assess the potential environmental impacts of a product/service throughout its life cycle [19-24,26]
LCCA	Method for evaluating all relevant costs over time of a project or a product [21]
Modelling and simulation	Process for building and operating a model to predict the effect of changes to a system [40,45]
MCDA	Framework for supporting decision-making with multiple and conflicting objectives [27]
Questionnaire	Data gather tool consisting of questions [46,47,49,52]

The selected indicators were analysed in accordance with the three dimensions of sustainability; i.e., economy, environment, and society. Almost all indicators addressed environmental aspects while only six indicators cover all three dimensions simultaneously with the social dimension the least well covered; e.g. including social aspects such as employment, safety and training [25,27,42,51-53]. The absence of well-developed social impact assessment frameworks is one of the reasons for the shortage of social sustainability indicators [12].

The data required for using the selected indicators was divided into six categories (Table 4). Design-related and environmental data is necessary for most of the selected indicators. For instance, the characteristics of the materials or components in a product from primary or secondary sources are the basis of circularity assessment in MCI. The details of a product design, such as the type of connection between two components, are essential for assessing the possibility of disassembly and remanufacturing.

Table 4. Required data for using the selected circularity indicators.

Data category – Examples of information	**Number of indicators**
Product – Design information, specifications, bill of materials, knowledge of product life cycle, etc.	29
Business operations – Business model, production data, supplier information, etc.	9
Social – Employment, working environment, training, social impacts caused by company, etc.	6
Financial – Revenue, material costs, logistics costs, packaging costs, etc.	20
Post-use product – EOL strategies, scenarios, recovery rates, collection/disassembly/recycling processes, etc.	25
Inventory database and environmental data – Life cycle inventory data, environmental impacts, material flows, resource consumption, waste generation, etc.	28

According to the experts at the case company, EOL data and life cycle inventory databases have not been well-developed in their company. Due to their current business model and the constraints from multiple stakeholders in the supply chain, and especially from their clients, they manufacture products under several fixed requirements. The data related to product use were not available or they would require a lot of efforts to acquire since they relate to activities beyond their control. Although the EOL stage is a key for closing the loop in CE, the associated data is often unavailable or uncertain. For instance, assumptions regarding collection and recycling rate or substitution ratio have to be made while assessing the environmental benefits derived from substituting virgin with recycled materials. Conversely, the data related to business operations, employment, and financial performance of a company is relatively easy to collect and manage.

3.2. Applying micro-level circularity indicators

A production line of food-grade plastic products was chosen to test the indicators. The recycling solutions for food-grade plastics must comply with stringent regulatory constraints regarding purity and contamination. In the company case, the client's requirements imposed the use of virgin material only. The product is composed of two parts made from a single material: polypropylene (PP). The manufacturing process starts with the virgin PP being fed into the injection moulding machine followed by transporting the moulded products for quality inspection with a conveyor belt. The OK parts are then sent to final assembly followed by packaging and transport to the clients. The defect rate is 1.2% with not OK (NOK) parts crushed and sold to waste management contractors.

Five waste management scenarios were created to test micro-level indicators and evaluate the overall circularity of the manufacturing system (or the product) with open-loop and closed-loop recycling of different waste streams (Fig. 1):

- Baseline scenario: virgin feedstock, NOK parts offsite recycling, EOL product disposal
- Offsite recycling and open-loop EOL recycling: virgin feedstock, NOK parts offsite recycling, EOL product recycling
- Onsite recycling: virgin feedstock, NOK parts onsite recycling, EOL product disposal
- Onsite recycling and open-loop EOL recycling: virgin feedstock, NOK parts onsite recycling, EOL product recycling
- Onsite recycling and closed-loop EOL recycling: 95% recycled feedstock, NOK parts onsite recycling, EOL product recycling

Most of the data required to perform the calculations were provided by the case company. The data related to the product EOL was not available, thus assumptions were made for the calculations. The five scenarios created covered a broad range of waste management strategies to fill this gap in the data. The five indicators selected for the case study were: Material Reutilization Score (MRS) [31], Circular Economic Value (CEV) [50], Product-Level Circularity Metric (PLCM) [32], Quantitative Indicators and Value Assessment (QIVA) [41], and MCI [14]. It is important to note that none of these indicators include an environmental impact assessment; they only measure the degree of circularity of the system analysed with higher values indicating higher degree of circularity.

Material Reutilization Score (MRS). This indicator was developed to assess the material reutilization score of a product and to eliminate the concept of waste [31]. It is the ratio of secondary material content and recyclable or biodegradable content in a product. Calculations at the case company showed that there is a small difference between onsite and offsite production waste recycling scenarios due to the low defect rate of the production line. But when considering the closed-loop EOL recycling, the MRS value drastically increases since recycled material input are used to make the product. This trend in the results was observed for the other four indicators tested as well. However, due to the client's requirements, MRS was not able to identify opportunities which can be applied in the case company's manufacturing line as only virgin material is currently allowed.

Circular Economic Value (CEV). This indicator focuses on material and energy usage to help companies in identifying which circular strategy or group of strategies to implement. According to Fogarassy et al. [50], if CEV is 60% or higher, repair, reuse, reduce and refuse could be adopted. If CEV is 40% to 50%, remanufacturing and refurbish strategies are recommended. Finally, if CEV is 30% or less, then repurpose, recyle and recover strategies are suggested. Results from the case study show that the choice of EOL treatment of used products significantly affects the CEV: the scores for open-loop EOL recycling scenarios are almost twice higher than the EOL product disposal scenarios (respectively 63% and 38%). CEV was perceived as both usable and useful by the case company because the data needed for the calculations are easy to acquire and CEV aligns with one of the goals of the company, which is to implement circular strategies in their processes.

Product-Level Circularity Metric (PLCM). This indicator is defined as the ratio of recirculated economic value

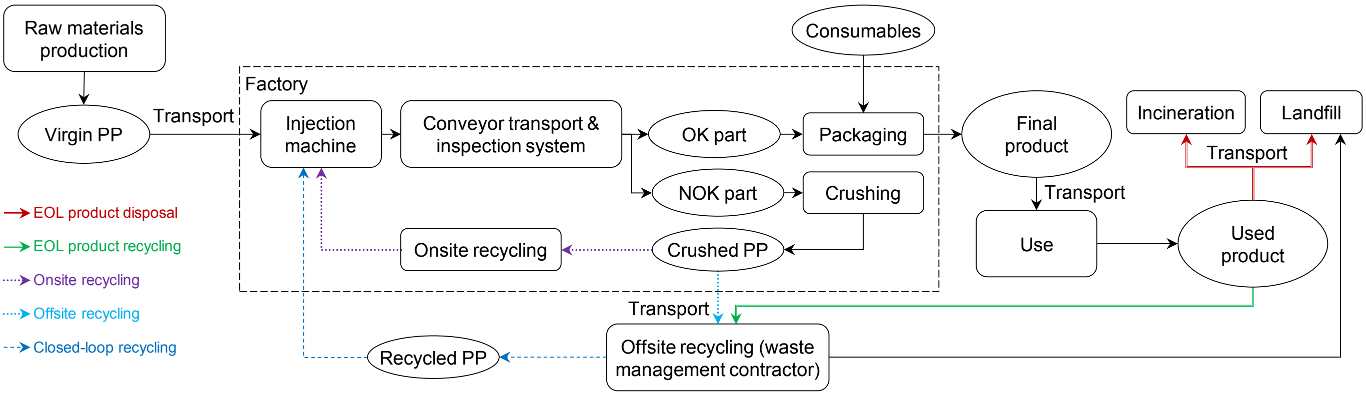

Fig. 1. Process and material flows with waste management alternatives for the different scenarios.

to total product value [32]. Thus, it is a value between 0 and 1. The price of polymers varies quickly and widely [55], thus this indicator should be recalculated with the current price for an accurate and up-to-date evaluation. The material cost for recycled PP was assumed to be the same as virgin PP (i.e., economically competitive recycling solutions). In the first two scenarios, all materials consumed were virgin materials, thus the product circularity was zero. In the next two scenarios, onsite recycling only slightly increases the content of recirculated materials (1.2% defect rate) as input into the manufacturing process. If the packaging material is 100% recycled, the score can further increase to 0.920 based on the last scenario (onsite + closed-loop EOL).

Quantitative Indicators and Value Assessment (QIVA). This set of indicators aims to identify areas of interventions in manufacturing processes [41]. It requires the production data; e.g., material flows going into the process and their characteristics, and relevant costs related to environmental management activities in a factory. Due to the lack of all data needed for QIVA, only the **Mass Recovery Index (MRI)** could be calculated. It is the ratio between the product output mass and the total material mass entered in a process. The MRI is the same in the baseline and offsite recycling scenarios due to the low production waste output. Due to the onsite recycling, the other three scenarios are able to achieve 100% of MRI.

Material Circularity Indicator (MCI). This circularity indicator has gained popularity in the last five years thanks for the Ellen MacArthur Foundation (EMF) and seem to be the most commonly used to date. The MCI calculation method is described in the EMF report [14]. MCI measures the extent to which the linear flow has been minimized and the circular flow maximized. This is done with a Linear Flow Index (LFI) and utility factor which was assumed to be 0.9 in all scenarios. MCI covers more aspects than the other four indicators tested; e.g., lifespan, recycling rate, and use intensity. Accordingly, it requires more data to deliver results and could be more difficult to use. From the results, recommendations for the production line included ecodesign measures (e.g., new design of a reusable product), development of acceptable recycled raw material, treatment process of NOK parts, etc.

Table 5 shows the calculation results for all tested indicators and scenarios. The scores obtained are pointing to different aspects of circularity. For all indicators, production waste recycling (onsite and offsite) only marginally improved the scores due to the low defect rate in the production line.

Table 5. Circularity indicators tested in the case study.

Recycling scenario	MRS	CEV	PLCM	MRI	MCI
Baseline	66.6	37.6%	0	98.8%	0.199
Offsite + open-loop EOL	66.6	62.6%	0	98.8%	0.533
Onsite	67.1	37.9%	0.012	100%	0.204
Onsite + open-loop EOL	67.1	62.9%	0.012	100%	0.538
Onsite + closed-loop EOL	98.3	84.6%	0.920	100%	0.966

Amongst the five indicators tested, PLCM and QIVA (MRI) were the only ones able to account for secondary materials consumed which are not part of the product (consumables). These two methods focus on different types of circular flows. PLCM measures circular inputs into the manufacturing process, thus production waste and product EOL management do not affect the score unless they are closed-loop recycling pathways. Conversely, MRI focuses on the value output and measures the amount of material consumed that is converted into a product. Only the CEV and MCI indicators were able to capture differences between all scenarios.

The workshop with the case company provided insights on what usefulness and usability criteria they would prioritise: measurability, data availability, strategic relevance, reliability, validity, compatibility and evolvability. The case company stated that the indicator needs to provide a circularity score (measurability) and the data needed for the calculation must be available or easy to obtain (data availability). The indicator must correctly represent their processes (validity) and with accurate and consistent results (reliability) to point to practical improvements and help implement CE in their operations. The compatibility and evolvability are also important to ensure that the company can integrate these indicators with existing and future performance management systems.

Finally, according to the results of the workshop, the case company was more interested in MCI and CEV than the other indicators. Due to the constraints imposed by their current business model, they were least interested in the MRS and PLCM as these indicators target aspects they cannot change, such as the material selection. However, the usefulness and usability of these indicators depend on the goals and business model of the case company (strategic relevance). Since the case company is an OEM whose clients take responsibility of the products, it is less likely to use indicators focusing on EOL strategies and would prioritise indicators pointing to manufacturing processes improvements.

4. Conclusion

This study reviewed 40 micro-level circularity indicators and tested five of them at a manufacturing company with five waste management scenarios. In the case study presented, environmental impacts were not assessed but should be considered in future work since increased circularity does not systematically result in increased environmental sustainability. Possible trade-offs or rebound effects must be accounted for to ensure that improved performance in one phase of the product or material life cycle is not offset by unintended negative consequences elsewhere in other life cycle phases. Instead, this study focused on the usability and usefulness of various indicators from a manufacturer's perspective.

The availability of primary data—especially bill of materials and product EOL information—and accurate secondary data—inventory database and environmental data—is the most critical usability criteria to deliver valid, reliable and actionable results about the circularity of a product or a company as key usefulness criteria. Furthermore, indicators' usefulness and usability are dynamic and can change according to the company's goals and business model. In addition, some indicators need to be updated regularly to ensure reliability and timeless in the information, for example material costs and advances in recycling technologies changing what is technically and economically feasible at a given time.

Manufacturing companies are increasingly aware of and interested in CE, thus seeking to integrate relevant indicators for performance assessment and operations management. This paper identified the type of information and desirable features making circularity indicators more usable and useful for a manufacturer. These findings can be generalised beyond the five indicators tested and can provide valuable insights to develop methods guiding the implementation of circularity indicators in manufacturing. The ability to capture variations in the manufacturing process and configurations of circular flows both upstream and downstream should be the basis to select and further develop micro-level indicators suitable for the specific needs and operating conditions of manufacturing companies.

Acknowledgements

The authors wish to acknowledge Marco Dias, Pedro Costa, Hugo Brandão and the team at GLN for their contribution. This work was supported by Chalmers' Area of Advance Production, the European Research Council (ERC) under grant no. 810764, the Swedish innovation agency Vinnova under grant no. 2019-00787 and the strategic vehicle research and innovation programme (FFI) under grant no. 2020-05180. The support is gratefully acknowledged.

References

[1] Tao F, Zhang M. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. IEEE Access 2017;5:20418–27.

[2] Strozzi F, Colicchia C, Creazza A, Noè C. Literature review on the 'smart factory' concept using bibliometric tools. Int. J. Prod. Res. 2017;55.

[3] Barricelli BR, Casiraghi E, Fogli D. A survey on digital twin: Definitions, characteristics, applications, and design implications. IEEE Access 2019;7.

[4] Felstead M. Cyber-physical production systems in industry 4.0. Econ. Manag. Financ. Mark. 2019;14:37–43.

[5] Despeisse M, Bekar ET. Challenges in Data Life Cycle Management for Sustainable Cyber-Physical Production Systems. In: IFIP Advances in Information and Communication Technology. 2020. p. 57–65.

[6] Yoon VY, Aiken P, Guimaraes T. Managing Organizational Data Resources: Quality Dimensions. Inf. Resour. Manag. J. 2000;13:5–13.

[7] Escobar CA, McGovern ME, Morales-Menendez R. Quality 4.0: a review of big data challenges in manufacturing. J. Intell. Manuf. 2021.

[8] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl. 2017;127:221-32.

[9] Kumar V, Sezersan I, Garza-Reyes JA, Gonzalez EDRS, Al-Shboul MdA. Circular economy in the manufacturing sector: benefits, opportunities and barriers. Manag. Decis. 2019;57:1067-86.

[10] Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A. A taxonomy of circular economy indicators. J. Clean. Prod. 2019;207:542-59.

[11] Kristensen HS, Mosgaard MA. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 2020;243:118531.

[12] Corona B, Shen L, Reike D, Rosales Carreón J, Worrell E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour Conserv Recycl. 2019;151:104498.

[13] De Pascale A. A systematic review for measuring circular economy: The 61 indicators. J. Clean. Prod.2021;281:124942.

[14] Ellen MacArthur Foundation. Circularity Indicators - An approach to measuring circularity - project overview. 2015.

[15] Di Maio F, Rem P. A Robust Indicator for Promoting Circular Economy through Recycling. J. Environ. Prot.. 2015;6: 1095-1104.

[16] Cullen JM. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? J. Ind. Ecol. 2017;21:483-6.

[17] Figge F, Thorpe AS, Givry P, Canning L, Franklin-Johnson E. Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. Ecol. Econ. 2018;150:297-306.

[18] Iacovidou E, Velenturf APM, Purnell P. Quality of resources: A typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example. Sci. Total Environ. 2019;647:441-8.

[19] Haupt M, Hellweg S. Measuring the environmental sustainability of a circular economy. Environ. Sustain. Indic. 2019;1-2:100005.

[20] Vogtlander JG, Scheepens AE, Bocken NMP, Peck D. Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing. J. Remanuf. 2017;7:1-17.

[21] Laso J, García-Herrero I, Margallo M, Vázquez-Rowe I, Fullana P, Bala A, et al. Finding an economic and environmental balance in value chains based on circular economy thinking: An eco-efficiency methodology applied to the fish canning industry. Resour Conserv Recycl. 2018;133:428-37.

[22] Niero M, Kalbar PP. Coupling material circularity indicators and life cycle based indicators. Resour Conserv Recycl. 2019;140:305-12.

[23] Scheepens AE, Vogtländer JG, Brezet JC. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. J. Clean. Prod. 2016;114:257-68.

[24] Huysman S, Debaveye S, Schaubroeck T, Meester SD, Ardente F, Mathieux F, et al. The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. Resour Conserv Recycl. 2015;101:53-60.

[25] Ameli M, Mansour S, Ahmadi-Javid A. A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. Resour Conserv Recycl. 2019;140:246-58.

[26] Huysman S, De Schaepmeester J, Ragaert K, Dewulf J, De Meester S. Performance indicators for a circular economy: A case study on post-industrial plastic waste. Resour Conserv Recycl. 2017;120:46-54.

[27] Alamerew YA, Brissaud D. Circular economy assessment tool for end of life product recovery strategies. J. Remanuf. 2019;9:169-85.

[28] Cong L, Zhao F, Sutherland JW. A Design Method to Improve End-of-Use Product Value Recovery for Circular Economy. J. Mech. Des. 2019;141.

[29] Favi C, Germani M, Luzi A, Mandolini M, Marconi M. A design for EoL approach and metrics to favour closed-loop scenarios for products. Int. J. Sustain. Eng. 2017;10:136-46.

[30] Horvath B, Bahna M, Fogarassy C. The Ecological Criteria of Circular Growth and the Rebound Risk of Closed Loops. Sustainability. 2019;11:2961.

[31] Cradle to Cradle Products Innovation Institute. Material reutilization. Cradle to Cradle Certified Product Standard. Version 3.1; 2018. p. 48-54

[32] Linder M, Sarasini S, van Loon P. A Metric for Quantifying Product-Level Circularity. J. Clean. Prod. 2017;21:545-58.

[33] Di Maio F, Rem PC, Baldé K, Polder M. Measuring resource efficiency and circular economy: A market value approach. Resour Conserv Recycl. 2017;122:163-71.

[34] Franklin-Johnson E, Figge F, Canning L. Resource duration as a managerial indicator for Circular Economy performance. J.Clean. Prod. 2016;133:589-98.

[35] Cayzer S, Griffiths P, Beghetto V. Design of indicators for measuring product performance in the circular economy. Int. J. Sustain. Eng. 2017;10:289-98.

[36] Zwolinski P, Lopez-Ontiveros M-A, Brissaud D. Integrated design of remanufacturable products based on product profiles. J. Clean. Prod. 2006;14:1333-45.

[37] Lee HM, Lu WF, Song B. A framework for assessing product End-Of-Life performance: reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. J. Clean. Prod. 2014;66:355-71.

[38] Bovea MD, Pérez-Belis V. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. J. Environ. Manage. 2018;228:483-94.

[39] Mesa J, Esparragoza I, Maury H. Developing a set of sustainability indicators for product families based on the circular economy model. J. Clean. Prod. 2018;196:1429-42.

[40] Schaik A, Reuter M. Recycling indices visualizing the performance of the circular economy. World of Metallurgy - ERZMETALL. 2016;69:201-16.

[41] Soporan VF, Vescan MM, Lehene TR, Pădureţu S, Gabor T. Considerations regarding the recalibration of the manufacture of castings from the perspective of the development of the circular economy. IOP Conf. Ser.: Mater. Sci. Eng. 2020;877:012053.

[42] Golinska P, Kosacka M, Mierzwiak R, Werner-Lewandowska K. Grey Decision Making as a tool for the classification of the sustainability level of remanufacturing companies. J. Clean. Prod. 2015;105:28-40.

[43] van Loon P, Van Wassenhove LN. Assessing the economic and environmental impact of remanufacturing: a decision support tool for OEM suppliers. Int. J. Prod. Res. 2018;56:1662-74.

[44] Vanegas P, Peeters JR, Cattrysse D, Tecchio P, Ardente F, Mathieux F, et al. Ease of disassembly of products to support circular economy strategies. Resour Conserv Recycl. 2018;135:323-34.

[45] Marconi M, Germani M, Mandolini M, Favi C. Applying data mining technique to disassembly sequence planning: a method to assess effective disassembly time of industrial products. Int. J. Prod. Res.2019;57:599-623.

[46] Das SK, Yedlarajiah P, Narendra R. An approach for estimating the end-of-life product disassembly effort and cost. Int. J. Prod. Res. 2000;38:657-73.

[47] ResCoM (Resource Conservative Manufacturing) project. Circular Pathfinder. 2017.

[48] ResCoM (Resource Conservative Manufacturing) project. Circularity Calculator. 2017.

[49] Kingfisher. The Business Opportunity of Closed Loop Innovation. Westminster; 2014

[50] Fogarassy C, Kovács A, Horvath B, Bakosné M. The development of a circular evaluation (CEV) tool. Case Study for the 2024 Budapest Olympics. Hung. Agric. Eng. 2017:10-20.

[51] Rossi E, Bertassini AC, Ferreira CdS, Neves do Amaral WA, Ometto AR. Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases. J. Clean. Prod. 2020;247:119137.

[52] Azevedo SG, Godina R, Matias JCdO. Proposal of a Sustainable Circular Index for Manufacturing Companies. Resources. 2017;6:63.

[53] Veleva V, Bodkin G, Todorova S. The need for better measurement and employee engagement to advance a circular economy: Lessons from Biogen's "zero waste" journey. J. Clean. Prod. 2017;154:517-29.

[54] Udo de Haes HA. Applications of life cycle assessment: expectations, drawbacks and perspectives. J. Clean. Prod. 1993;1:131-7.

[55] British Plastics Federation. Polymer Price Index & Cost Comparison. https://www.bpf.co.uk/plastipedia/polymer_prices.aspx [accessed 2021-11-05]