Journal of Cleaner Production 445 (2024) 141289

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A methodology to assess circular economy strategies for sustainable manufacturing using process eco-efficiency

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ARTICLE INFO

Handling editor: Kathleen Aviso

Keywords:
Circular economy
Eco-efficiency
Life cycle assessment
Process
Sustainable manufacturing
Waste

ABSTRACT

A growing number of companies engage in sustainability, with early adopters already realizing financial and environmental benefits. However, the current linear production model followed by most manufacturers is widely recognized as not being sustainable. The circular economy model can be an eco-friendly alternative to production and consumption, ensuring a smooth transition to sustainable practices. In this study, the impact of various sustainable practices in manufacturing is reviewed as well as the impact of life cycle assessment in the quantification of the impact of the sustainable practices. However, a simple and fast methodology for manufacturers to get a first indication about the potential improvements in their production lines and required changes for adopting circular economy practices is missing from the literature. The main objective of this study is to provide a quantified methodology that facilitates decision-making at a manufacturing process and system level regarding the adoption of more sustainable strategies. An *eco-efficie*ncy indicator is proposed targeting the reduction of energy consumption and manufacturing waste caused by production operations, on top of the life cycle assessment and cost analysis of a process. The indicator combines a process's environmental performance, whose calculation is performed using life cycle assessment studies, and the process's value performance, whose calculation is derived from a combination of a life cycle costing analysis with the process and product-related metrics encapsulated under the umbrella of the overall equipment effectiveness, and of a cost of implementation metrics signifying the required cost for replacing existing equipment to adopt a circular economy strategy. Additionally, the indicator is not constrained by any geographical coverage and applies to any manufacturing use case as long as the life cycle assessment model is constructed using the ISO 14044:2006 standard. The proposed approach is examined in two industrial use cases, in which the proposed indicator is evaluated against three potential circular economy strategies for improved sustainability, the use of renewable energy sources, and material reuse.

1. Introduction

A manufacturing system can be defined as a combination of people, equipment, and procedures organized to accomplish the manufacturing objectives of a company, bound by a common material and information flow (Chryssolouris, 2006). Traditionally, raw material is converted into a manufactured product, which after its useful life is discarded (Chryssolouris et al., 2008). This linear model is followed by most manufacturers, resulting in the generation of waste with significant environmental and societal impact. However, the rising prices of raw materials, the increase in the global demand for energy and resources, the increasing complexity of supply chains, and public concern about environmental issues, require more sustainable practices (OECD, 2021). This can be achieved by transitioning from a linear economic model to a closed-loop or circular economy paradigm (Winkler, 2011), where, for example, disposed materials are restored and used in multiple industrial cycles, and renewable energy sources replace fossil fuels. Such circular models make the manufacturing process more energy and cost-efficient than its linear counterpart.

The concept of sustainability in the manufacturing industry has been

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https://doi.org/10.1016/j.jclepro.2024.141289
Received 20 September 2023; Received in revised form 12 February 2024; Accepted 14 February 2024
Available online 19 February 2024

highly documented and the United Nations (UN) has provided a plan for sustainable development up to 2023 (Transforming our world: the 2030 Agenda for Sustainable Development, 2015). In Schroeder et al., 2019), it has been identified that the adoption of circular economy practices can aid the achievement of several sustainable development goals (SDGs) detailed in the 2030 agenda provided by the UN. In more detail, the adoption of such practices contributes towards the achievement of SDG6 (clean water and sanitation), SDG7 (affordable and clean energy), SDG8 (decent work and economic growth), SDG12 (responsible consumption and production) and SDG15 (life on land). Additionally, a similar conclusion was made in Belmonte-Ureña et al., 2021).

In recent years, sustainable practices have been adopted across the manufacturing industry to promote circularity, such as renewable energy sources (Pablo-Romero et al., 2022), the use of LCA to evaluate alternative circular practices (Bjørnbet and Vildåsen, 2021) and altering product design based on eco-design principles (Trollman et al., 2020). Additional practices include the introduction of carbon footprint management techniques across the supply chain (Ghosh et al., 2020), the adoption of lean manufacturing principles (Maware et al., 2022) and by enforcement of zero-waste practices (Awogbemi et al., 2022).

Emerging fields are providing alternatives to promote sustainability in manufacturing, such as the use of nanomaterials, biofuels, green initiatives in battery production and the use of renewable energy and solar fuels (Huang, 2021; Pablo-Romero et al., 2022; Katiyar and Goel, 2023). In Lin et al., 2023), strategies for recycling batteries are reviewed and technologies are proposed to enhance carbon neutrality. Colombo et al. (2023) promote eco-design in battery manufacturing by proposing a novel cathodic material for lithium-sulfur batteries due to its high specific capacity, low cost, and low environmental impact. In addition, Maka and Alabid (2022) studied the effects of renewable energy sources on sustainable development and presented a strategy for future development. In the context of solar fuels green hydrogen initiatives have proven fundamental towards the promotion of sustainability (Megía et al., 2021). Related to hydrogen production, in Serrano-Jiménez et al., 2023) the feasibility of the electrochemical reforming of a real industrial fusel oil production of renewable hydrogen addressing a circular economy model was demonstrated. According to Kabir et al. (2023) the effect of machine learning is proven substantial in optimizing green hydrogen production which can be used in solar fuels. Furthermore, novel practices in chemistry have proven determinantal towards the improvement of sustainability across industries. In Eisa et al., 2022) challenges related to nitrogen fertilizer production are discussed and the potential for zero-waste is explored through the use of waste products. Lastly, in Verma et al. (2023), the usage of nanocomposites such as urea-hydroxyapatite nanohybrid is discussed and its advantages in promoting sustainability in the agricultural sector.

Implementing circular economy strategies in manufacturing takes time, planning, and investment, which may pay off in the long term (Diaz et al., 2022). Advanced digital solutions may be used to reduce energy consumption and costs, thus the carbon footprint, improve productivity and reduce defects and waste, water, and raw material (Aivaliotis et al., 2021; Alexopoulos et al., 2023). Additionally, with machine learning methodologies, a production environment can be optimized to enhance its sustainability (Kabir et al., 2023). However, it is challenging for manufacturers to identify improvements in their production systems in a fast and comparative approach, facilitating further in-depth investigation and decision-making (Draghici and Ivascu, 2022).

Hence, this study aims to support manufacturers in quantifying their transition to green manufacturing, by providing a quantified indicator calculated through an LCA-based methodology to easily and quickly compare alternative circular economy interventions to their manufacturing processes. The study's objective is to provide a methodology that facilitates decision-making in the context of adopting a circular economy strategy, through the main contribution of this work which is to provide a framework for manufacturers to quantitively assess alternative circular economy, strategies at a manufacturing process level and a system level to fill the gap in the literature where an indicator that quantifies the transition to sustainable practices by coupling the gains in terms of environmental and economic sustainability for a manufacturer is missing. An extended *eco-efficiency* indicator is proposed as part of a methodology for manufacturers to evaluate the adoption of alternative circular economy strategies, starting from individual processes, but extending to the overall system by utilizing data at the manufacturing process level. This allows manufacturers to evaluate their contribution towards achieving SDG12, specifically SDG12.2 (achieve the sustainable management and efficient use of natural resources), SDG12.5 (substantially reduce waste generation through prevention, reduction, recycling and reuse) and SDG12.6 (encouragement of companies to adopt sustainable practices).

The proposed indicator is calculated on top of a process life cycle assessment (LCA) and life cycle cost (LCC) analysis. Given that the proposed indicator is calculated on top of a process LCA and LCC, it is applicable to any manufacturing use case, when the LCA is conducted following the ISO 14044:2006. Nevertheless, in case an LCA model of a manufacturing process or system is built not in accordance with the ISO, then the methodology is still applicable, however, the results obtained may not be accurate. Three circular economy strategies are investigated in the context of two industrial use cases, 1) the use of renewable energy sources in the energy sources mix, 2) material reuse, and 3) both the use of renewable energy sources and material reuse. The extended indicator considers three main parameters per process and for a specific time horizon, including the product/service value stemming from the specific process, its environmental impact, and the defects generated from the process in the specific time horizon.

2. Literature review

2.1. Sustainable manufacturing and circular economy strategies

Sustainable manufacturing plays a major role in reducing negative environmental impacts, developing social welfare, and contributing to sustainable economic growth, as discussed in Johansson et al. (2019). Its core idea is to create products through economically sound processes that minimize potential environmental impacts (Armstrong et al., 2023). In that context, researchers have found that significant energy wastes can be reused, through waste heat recovery, combined heat and power, thermal storage, and more, thus following the circular economy paradigm. The three key principles enabling circular economy include a) eliminating waste and pollution, b) circulating products and materials at their highest value, and c) regenerating nature (What is a circular economy). The major objective of the circular economy is to use 100% recycled or re-used content in a product. Such a goal needs to be checked in terms of considering the impacts of energy, water, and material use of obtaining and safely using recycled materials (Peña et al., 2021).

Otto et al. (2017), studied the effect of the integration of renewable energy and hydrogen into the German steel industry, thus reducing CO_2 emissions. The specific research focused on the outcome of integrating techniques such as blast furnace gas recirculation (BF-GR), furnaces that utilize carbon capture, a higher share of electric arc furnaces, and the use of direct reduced iron with hydrogen as a reduction agent (H-DR). Their research concluded that, in the German steel industry, the incorporation of such techniques could lead to reductions of up to 95% of CO_2 emissions against 1990 levels and up to 95% reduction of primary energy demand against 2008. Furthermore, Serrano-Jiménez et al., 2023, demonstrated the feasibility of the electrochemical reforming of a real industrial fusel oil production of renewable hydrogen addressing a circular economy model. Similarly, Vinci et al., 2019, showed that the emissions derived from the production of glass bottles and containers could be further decreased by reducing the energy used during the production phase of glass through the reuse of hot air coming out of the melting furnace in a production line. Glass containers have demonstrated being a good environmental choice for packaging foods and beverages, especially with increasing recycled content rates. It is a noteworthy observation, considering that the average glass recycling percentage in Europe was 76% in 2020 ("EU-27", 2023).

To check the environmental impact of energy, water, and material use of any recycled, re-used, renewed, refurbished, repurposed, or new product, the European Union together with the Enel Group in 2020 defined a set of parameters and indicators used to quantify the circularity of products and projects, based on the benefits of reducing virgin materials consumption (A Journey into the Enel Group's Circular Economy). These parameters were among others CO2 emissions, water consumption, impact on soil, impact on freshwater, impact on seawater, and impact on human toxicity. All these parameters can be obtained through an LCA study conducted according to the ISO 14040 standard (2006).

Several questions derive from decision-making on circular economy strategies, which can be answered by the application of LCA and its related methodologies. Such questions are explored by Peña et al. (2021). In addition, several studies have indicated that the process of adopting circular economy strategies needs to be gradual (Khan et al., 2022). Furthermore, it has been shown that in various industries like the agriculture sector, the adoption of circular economy policies has been gradual since factors such as in most implementations of circular economy in the industry have encountered issues in promoting social sustainability as documented in Castillo-Díaz et al. (2023). Lastly, similar results have been drawn in Escribano et al. (2015) in the context of the beef industry and in Baumer-Cardoso et al. (2023), in the context of the manufacturing industry.

2.2. LCA for circular and sustainable manufacturing

LCA can be used for assessing the environmental performance (EP) of a product design as it is a methodology for assessing the environmental impacts of products throughout their lifecycle (Delaney et al., 2022), but also for large-scale changes like companies making a shift towards circular economy according to Haupt and Zschokke (2017); Haupt and Zschokke (2017), concluded that through the evaluation of the environmental impact of products throughout their lifecycle and processes, with LCA, it can be ensured that circular strategies align with the goal of reducing environmental impacts which is essential in the circular economy. LCA gives a guarantee for the development of sustainability in all industries (Ranjan et al., 2021). Vinodh et al. (2016), proposed a framework for value stream mapping integrated with LCA to ensure sustainable manufacturing. Gallucci et al. (2021), conducted a cradle-to-grave LCA study by doing a comparative analysis of different scenarios using seven environmental impact indicators. Some studies on possible improvements by using LCA-associated indicators are listed in Table 1.

Table 1
Possible improvements shown by LCA studies.

Reference	LCA associated	Industry	Results
Dorn et al. (2016)	Key performance indicators (KPIs) + LCA	Microwave furnace production	Overall energy consumption can be reduced by up to 50%
Ferreira et al. (2016)	LCA	Thermo-modified pine board	75% of the impact on sustainability is due to energy consumption.
Renzulli et al. (2016)	Cradle-to-casting plant gate LCA	Solid steel slab production	Solid waste could be reused as raw materials in other industries
Tua et al. (2020)	LCA	Glass bottles reuse	Better environmental performance after two deliveries
Chen et al. (2022)	LCA	Lithium-ion battery (LIB)	Carbon emissions could be lowered by 51.8% with the use of remanufactured batteries.
Broadbent (2016)	LCA	Steel production	For each kg of steel scrap, 1.5 kg CO_2 eq. emissions, 13.4 MJ of primary energy, and 1.4 kg of iron ore are saved.
Shanbag and Manjare (2020)	LCA	Tyre manufacturing	It was identified that there are significant emissions of sulfur dioxide and nitrogen dioxide.
Kazan et al. (2020)	LCA	Woven shirt production	Using cotton fibres as the raw material decreased eutrophication, acidification, abiotic depletion, and global warming potential by 96%, 90%, 69%, and 47%, respectively.

The most crucial and time-consuming part of an LCA study is the life cycle inventory (LCI) phase. The purpose of LCI is the collection of data, mainly inputs and outputs which may include energy, raw materials, and respective emissions to air, water, soil, solid waste generation, products, and co-products (Laca et al., 2011). Zendoia et al. (2014), proposed an LCI method with four main steps. The first step includes the definition of the specification of the manufacturing process plan for a part or product. In the second step, the use scenario of a machine is defined as a sequence of different operating states. The third step includes the quantification of the environmental aspects through monitoring the flow of energy, materials, and substances. Step four focuses on the calculation, per machine and on the overall process, of overall resources and waste streams. Although there might be higher uncertainties with the use of the input-output LCI method, according to Islam et al. (2016), it is the least complex of all the LCI methods and provides fewer truncation error possibilities and calculates upstream or indirect environmental impacts compared to other LCI methods. However, Panagiotopoulou et al., 2022, conclude that the reduction of carbon emissions, which is a vital part of circular economy, can be done by identifying the tunable parameters at processes, machine, and system levels, from the material, machine tool, and energy point of view.

2.3. Eco-efficiency analysis

The separation of life cycle environmental assessment from economic analysis has limited the influence and relevance of LCA for decision-making (Norris, 2001). Eco-efficiency analysis harmonizes and bridges the gap between life cycle environmental assessment and economic analysis. The *eco-efficiency* indicator is the ratio between the economic value and the environmental impact caused by the product (Huppes and Ishikawa, 2005; Dreyfus et al., 2022). The eco-efficiency improves when the environmental impact is reduced and this reduction is maintainable or when the economic value of the said product is increased while the environmental impact remains unaltered (Picazo-Tadeo et al., 2011). However, in manufacturing this is not the case since environmental sustainability and economic sustainability are inversely related as indicated in Castillo-Díaz et al. (2023).

Park et al. (2007), used product quality as the product value and quantified it by following three steps. The first step was the normalization based on a value function, the second step was the determination of the subjective weighting factors of the attributes and the last step was the calculation of product quality of the chosen products. Afrinaldi (2022), proposed a new method for measuring eco-efficiency. In his publication, the economic contribution of a product is calculated using the input-output method, while the environmental impact is measured through a life cycle assessment analysis. Liu et al. (2019), adopted the SBM-Undesirable model to evaluate the eco-efficiency of the circular economy system in a coal mining area in China. In their research, energy flow indices are treated as input and output indices. In Laso et al., 2018), a two-step eco-efficiency methodology assessment for the fish canning industry is proposed combining LCA and LCC.

Sustainable manufacturing and the concept of circular economy can be linked together using indicators like eco-efficiency. Richa et al. (2017), proposed a circular economy-inspired waste management hierarchy for end-of-life LIBs from electric vehicles (EVs) and with the use of eco-efficiency metrics evaluated the potential environmental and economic trade-offs that may result from managing 1000 end-of-life EV battery packs in the United States. Figge and Thorpe (2023), through their research, bring operational eco-efficiency, circular economy, and sufficiency together under one coherent model. From their analysis, it is shown that eco-efficiency and circular economy principles follow the same basic concept of 'doing more with less'. This further justifies the findings of Geng and Doberstein (2008), who link the sustainable forms of development in a circular economy with the overall eco-efficiency of economic systems.

Failures during production increase the economic and environmental impact of the overall manufacturing process. Many strategies are being tested to reduce failures within production processes and eliminate product defects. Zero-defect manufacturing (ZDM) focuses on one of the main pillars of circular economy: the reduction of the environmental impact of a process as it pushes for the reduction of waste, reduction of generated scrap, and reduction of energy consumption (Cerquitelli et al., 2021; Kiritsis et al., 2021; Patil et al., 2019). ZDM has demonstrated improvement in sustainability without compromising performance, and it has even led to improvements in quality inspection (Psarommatis et al., 2022). Nowadays, the product life cycle has been reduced to capture market needs with the shift from mass production to mass customization. With the rise of product customization and personalization, batch sizes have significantly decreased and, consequently, there has been an increase in production defects due to the limited time available for optimizing the production process (Ojha et al., 2007).

To sum up, it can be supported by the conducted literature review that the application of LCA and LCA-based approaches in manufacturing can be used to enable sustainable manufacturing as presented in Table 1. Furthermore, the coupling of environmentally sustainable practices with the ones for economic sustainability is possible using the eco-efficiency indicator. However, based on the reviewed literature a gap is identified in decision-making for manufacturers to get a first indication of the potential improvements in their production lines and required changes for adopting circular economy practices, thus an extended eco-efficiency indicator is proposed which retains the environmental sustainability aspect of the existing indicator while extending it to encapsulate additional aspects of economic sustainability.

3. Methodology

To promote sustainable manufacturing, companies must reduce the environmental impact caused by each process of their production line. This eco-friendly mentality needs to be accompanied by an associated economic impact on the product under development. In this context, this study suggests the use of an extended *eco-efficiency* indicator, as illustrated in Fig. 1 and analyzed in the following paragraphs.

Starting from the standardised *Eco-efficiency* indicator, it can be calculated according to the equation presented hereafter:

$$Eco - efficiency = \frac{product\ or\ service\ value}{environmental\ performance/impact} \tag{1}$$

where.

- 'Product or service value' refers to the value performance (VP) of each process (Michelsen et al., 2006),
- 'Environmental performance/impact' refers to the total amount of environmentally harmful emitted substances and can be quantified through the EP metric that derives from the LCA (Michelsen et al., 2006).

The system boundaries of both LCA and LCC analysis are defined only for the individual production process under investigation and following the ISO 14044:2006 standard for environmental management and LCA. The creation of the LCA model should follow the ISO 14044:2006 standard and any software used for this purpose should comply with it.

The EP of a single process, in a production line, with m types of emissions that have environmental impact (e.g. NOx or CO2) can be calculated using the following equation:

$$EP = \sum_{x=1}^{m} \frac{E_x \times W_x}{N_x} \tag{2}$$

where.

- *EP*: is the environmental performance,
- *x*: is a substance that contributes to the environmental impact in terms of the global warming process,
- E_x: are the total emissions of a substance x (kg),
- W_x: is the weighting factor of substance x which is provided by the intergovernmental panel on climate change of the UN (IPCC,) and,

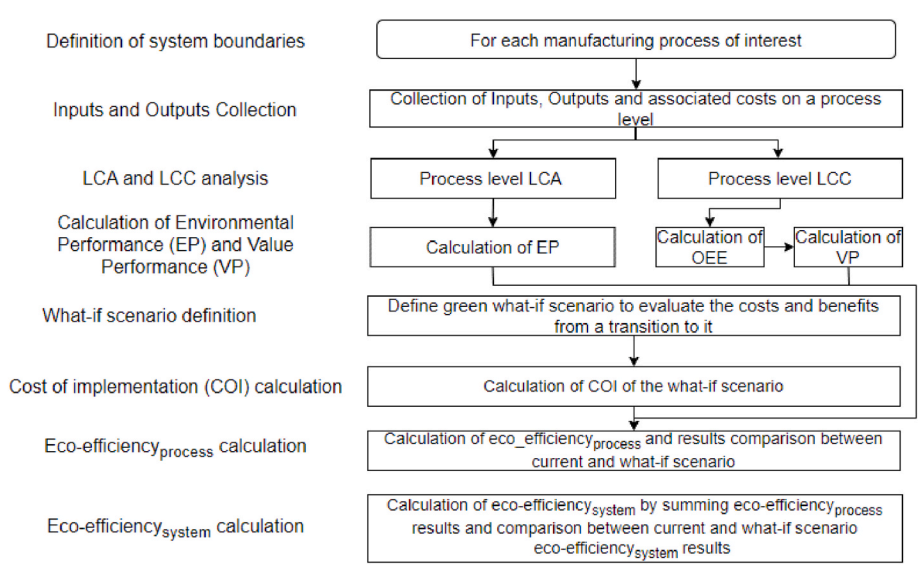

Fig. 1. Methodology to calculate the proposed extended eco-efficiency indicator.

- N_x: the normalization factor (kg CO_2 eq.).

The 'product or service value' or VP can be obtained through the LCC of the individual process contributing to the manufacturing of the product. Process LCC is defined as the cost accompanying each input and output of a process. Furthermore, as discussed by Michelsen et al. (2006), $\frac{1}{LCC}$ is the VP indicator.

However, because LCC only considers the monetary costs of the process, additional factors should be considered. These factors can be described using the overall equipment effectiveness (OEE) metric, which includes the availability, the performance, and the quality of the process. The formulas that calculate the availability, performance, and quality can be found in equation (3), equation (4), and equation (5), respectively, and the OEE formula can be found in equation (6).

$$Availability\ (A) = \frac{Run\ time}{Planned\ production\ time} \tag{3}$$

$$Performance\ (P) = \frac{Ideal\ cycle\ time \times Total\ count}{Run\ time} \tag{4}$$

$$First\ Pass\ Yield\ Rate = \frac{Good\ count\ or\ Quality\ units}{Total\ count\ or\ Total\ units\ produced} \tag{5}$$

$$OEE = A \times P \times FPYR \tag{6}$$

where.

- *Run time* denotes the time during which a process produces an output,
- *Planned production time* denotes the planned running time of a process under normal conditions,
- *Ideal cycle time* denotes the fastest cycle time that a process can achieve under optimal conditions,
- *Total count* denotes the total number of products produced by a single process during run time,
- *Good count* denotes the total number of products produced by a process that meet the predefined quality standards,
- *First pass yield rate* denotes the quality metric in the OEE formula and can be also expressed as the first pass yield rate (FPYR). The FPYR metric encapsulates the targeted quality of the process, with the maximum value achieved in the case of ZDM since the number of defective products is minimized.

Moreover, when considering the previously described parameters, the VP indicator can be provided by the following equation:

$$\mathrm{VP} = \frac{OEE}{LCC} = \frac{A \times P}{LCC} \times FPYR = \frac{A \times P}{LCC} \times \frac{Quality\ units}{Total\ units\ produced} \tag{7}$$

In addition, for a manufacturing company to realize a certain circular economy strategy, additional investment may be required, for example for introducing alternative energy sources to a production system additional infrastructure may be needed. This is considered in the current study as an additional 'set up' cost. Moreover, the downtime cost needs to be considered as well. The downtime cost refers to the financial losses of a company as a direct result of planned or unplanned downtime. These two costs can be combined in a cost of implementation (COI) metric calculated from the following equation:

$$COI = Setup\ cost + Downtime\ cost \tag{8}$$

By combining equations (1), (2), (7) and (8), the existing indicator can be calculated on a process level through the proposed *eco-efficiency$_{process}$* indicator, which is a dimensionless quantity, calculated through the following equation:

$$Eco - efficiency_{process} = \frac{\frac{A \times P}{LCC}}{\sum_{i=1}^{n} \frac{E_i \times W_i}{N_i}} \times \frac{Quality\ units}{Total\ units\ produced} \times COI \tag{9}$$

Thus, considering a system with n manufacturing processes, in which all processes are of interest for evaluating alternative circular economy strategies, the extended *eco-efficiency* on a system level, denoted as *eco-efficiency$_{system}$*, can be calculated as the sum of the individual extended *eco-efficiency$_{process}$* values as presented in the following equation:

$$Eco - efficiency_{system} = \sum_{i=1}^{n} \frac{VP_i}{EP_i} COI_i \tag{10}$$

where.

- : the individual process,
- VP_i: the VP of the individual process,
- EP_i: the EP of the individual process,
- COI_i: the COI of each process.

Hence, using equations (9) and (10), the proposed indicator can be calculated based on the present production values and costs. Considering that alternative circular economy strategies may differentiate production costs and/or values, the extended *eco-efficiency$_{process}$* and indicator can provide a metric to compare alternative circular economy strategies for individual manufacturing processes and groups of processes. Furthermore, the *eco-efficiency$_{system}$* can provide a metric for comparison regarding the entire manufacturing system which mandates the calculation of the *eco-efficiency$_{process}$* for all processes included in the system. As a result, and using advanced simulation tools and decision support methods, 'what-if' scenarios can be evaluated in a cost-effective and automated approach, evaluating the costs and benefits from a transition to greener practices, such as using renewable energy sources, recycled materials, or both circular economy strategies.

4. Industrial use cases and results

The proposed method has been tested in two industrial use cases related to a) glass bottle production and b) steel parts production. The study aims to assess the feasibility of the method as well as the validity of the extended *eco-efficiency* indicator. In both use cases, three circular economy strategies were considered, 1) renewable and alternative energy sources, 2) reuse of materials, and 3) a combination of 1) and 2).

The system boundaries of the LCA and LCC analysis are defined to cover only the production processes of the two use cases and for each scenario investigated, while considering geographical boundaries, in line with the ISO 14044:2006 for environmental management and LCA. The collection of input and output of LCI data was also carried out following the same standard, along with the construction of the LCA and LCC models as well as the collection of the cost information. The latter, however, were calculated based on the average price of each input and output during a month.

Next, the proposed *eco-efficiency* indicator is calculated based on equation (9) and equation (10). Regarding the COI and FPYR calculations and due to confidentiality reasons of the actual values, the following assumptions are considered.

- The COI is not considered in the manufacturing of glass bottles use case.
- The COI is included in one of the processes in the steel parts use case.
- The value of the FPYR was set to 96% for both cases.

4.1. Manufacturing of glass bottles

The main raw material used in the production process is flint glass.

The production processes that are investigated in this study are IR inspection, which produces thermal images of the glass containers as they are transported from the forming machine, and annealing lehr, which is responsible for relieving residual stresses from the glass containers due to temperature variations within the glass. The production plant has a conventional energy supply from the power grid, which is predominantly powered by fossil fuels. The type of raw material used as well as the energy supply are the main contributors to the environmental impact of the production plant as they generate greenhouse gases. The main greenhouse gases being generated from the glass bottle manufacturer include CO_2, CO, NO_x, N_2O, NH_3 and SF_6.

For the glass bottle industry, LCA analysis was conducted in the current production state for three hypothetical scenarios.

1) using a solar thermal power source instead of the power grid,
2) using recycled glass cullet instead of flint glass, and
3) using both strategies.

LCA and LCC analysis was performed for all three scenarios as well as the current status. Based on the LCA and LCC analysis results, the EP and VP were calculated for each process in the production line of the glass bottle manufacturer for all four strategies based on equations (2) and (7), respectively. Using equations (9) and (10), the *eco-efficiency* indicator of the individual processes and of the system were calculated.

The calculations for the EP were performed using the calculated mass of each emitted substance provided by the GaBi Software (Life Cycle Assessment Software,). The weighting factors were retrieved from the 2.10.2 Direct Global Warming Potentials - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and Radiative Forcing (Solomon et al., 2007). The normalization factor needed for the EP calculation is necessary to make the results comparable. As a normalization factor, the total kilograms of emissions of CO_2 eq. in the manufacturing sector of the country in which the glass bottle manufacturer is located for the year 2021 was used. Furthermore, the VP was calculated using an LCC analysis, where only the cost of the input and output flows of each process was used. Lastly, in the VP calculation, the availability and performance were both estimated to be 95%.

The results are presented in Table 2 along with the value of the proposed *eco-efficiency* indicator per strategy.

Hence, Table 2 and more specifically the results on the system level indicate that, by implementing both strategies the *eco-efficiency* indicator improves. Thus, in the case of the glass bottle manufacturer, the best policy for achieving sustainability and green manufacturing is the one where both recycled materials and electricity from renewable energy sources are used. It should be noted that, if the manufacturer selects only renewable energy as the main power source, the gains in terms of VP are minimal. However, the impact on the environment is reduced to half, due to the high reduction in CO_2-generated emissions.

To achieve gains in terms of VP and in terms of reducing its environmental footprint, the manufacturer should adopt both policies. This can also be seen in Fig. 2, and looking at the *eco-efficiency* indicator.

In practice, this can be justified due to the high reduction in costs that derive from using recycled glass instead of raw materials, as well as the decrease in emissions that derive from using renewable energy as the main power source.

Table 2
EP, VP, and extended eco-efficiency results.

	Process	Current	1 - Renewable energy	2 - Recycled material	3 - Combination of 1 and 2
Environmental performance					
1	IR inspection	2.13E-11	1.09E-12	2.13E-11	1.09E-12
2	Annealing lehr	1.91E-11	1.89E-11	1.91E-11	1.89E-11
	System	4.04E-11	2.00E-11	4.04E-11	2.00E-11
Value performance					
	System	0.00352	0.00353	0.006	0.006
Eco-efficiency					
1	IR inspection	0.867E+8	1.69E+9	1.77E+8	3.45E+9
2	Annealing lehr	0.878E+8	0.887E+8	1.21E+8	1.22E+8
	System	0.872E+8	1.76E+8	1.50E+8	3.03E+8
	System (%)		201.82%	172.01%	347.45%

4.2. Trailing suspension arm manufacturing use case

This use case concerns 13 processes, presented in Table 3, in which the main environmental impact, investigated in this study, is the emission of greenhouse gases from energy consumption along with waste generated during production. The main greenhouse gases generated include CO_2, CO, NO_x, N_2O, NH_3, HCL and HF. Additionally, the wastes include raw materials waste (deformed steel scrap) and consumables like paint.

As a first step, the LCA analysis of the processes was conducted, and the proposed *eco-efficiency* indicator was calculated. The same analysis was performed concerning the following three circular economy strategies.

1) using electricity generated from wind energy instead of the national grid,
2) using recycled steel instead of raw materials,
3) using both renewable energy and recycled material.

Next, the following values were calculated: a) the EP, b) the VP, c) the *eco-efficiency* for each process (Table 3), and d) the estimated COI for the heating process 2 (Table 4).

Again, the calculation of EP was performed with the use of the GaBi software. The software was used to provide the mass of each substance emitted in every process. Consequently, the weighting factors were taken from Solomon et al. (2007). Regarding the normalization factor the total kilograms of emissions of CO_2 eq. in the manufacturing sector of the corresponding country and for the year 2021. The VP was calculated based on the LCC analysis conducted in the trailing suspension arm manufacturing industry and took into consideration only the

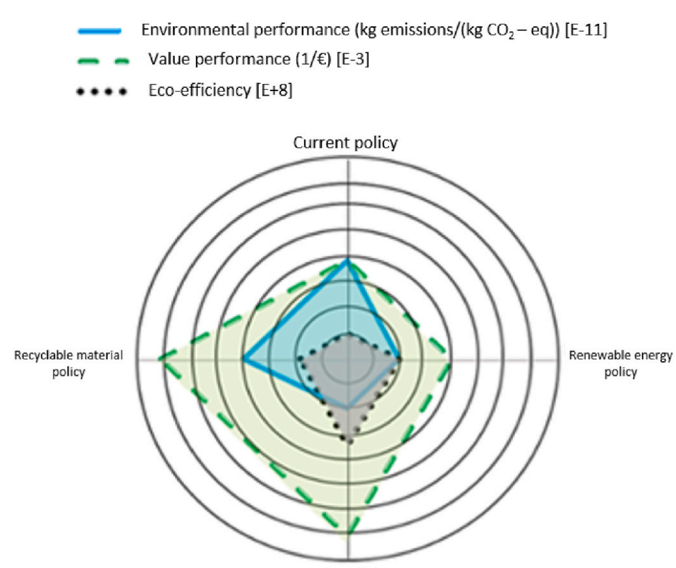

Fig. 2. Performance illustration for alternative circular economy strategies in glass manufacturing.

Table 3
EP, VP, and extended eco-efficiency results.

	Process	Current	1 - Renewable energy	2 - Recycled material	3 - Combination of 1 and 2
Environmental performance					
1	Heating process 1	4.18E-11	1.19E-12	4.18E-11	1.13E-12
2	Surface treatment process	8.84E-13	2.51E-14	8.80E-13	2.51E-14
3	Forming step 1	5.49E-12	1.56E-13	5.49E-12	1.13E-13
4	Forming step 2	1.05E-13	2.99E-15	1.05E-13	2.99E-15
5	Forming step 3	4.81E-13	1.47E-14	5.18E-13	1.35E-14
6	Forming step 4	3.11E-13	8.85E-15	3.11E-13	8.87E-15
7	Forming step 5	4.03E-12	1.15E-13	4.04E-12	1.60E-13
8	Heating process 2	7.59E-14	2.17E-15	7.60E-14	2.17E-15
9	Heating process 3	1.98E-11	1.92E-11	1.99E-11	1.85E-11
10	Heating process 4	6.03E-13	1.72E-14	6.04E-13	1.72E-14
11	Heating process 5	3.45E-11	9.83E-13	3.45E-11	9.47E-13
12	Heating process 6	3.08E-12	8.75E-14	3.08E-12	8.76E-14
13	Painting	1.59E-12	9.73E-13	1.59E-12	9.30E-13
	System	1.13E-10	2.22E-11	1.13E-10	2.19E-11
Value performance					
	System	100.06	106.65	100.09	123.19
Eco-efficiency					
1	Heating process 1	-	-	-	-
2	Surface treatment process	1.75E13	6.18E14	1.76E13	6.18E+14
3	Forming step 1	-	–	–	–
4	Forming step 2	1.11E13	3.90E14	2.57E13	9.08E+14
5	Forming step 3	–	–	–	–
6	Forming step 4	1.23E13	4.33E14	2.85E13	1.01E+15
7	Forming step 5	–	–	–	–
8	Heating process 2	–	–	–	–
9	Heating process 3	2.34E11	2.41E11	2.33E11	2.50E+11
10	Heating process 4	5.03E13	1.76E15	5.02E13	1.76E+15
11	Heating process 5	9.02E11	3.17E13	9.02E11	3.29E+13
12	Heating process 6	3.80E12	1.34E14	3.80E12	1.34E+14
13	Painting	1.12E12	1.84E12	1.13E12	1.93E+12
	System	8.86E11	4.80E12	8.86E11	4.87E12
	System (%)		543.00%	100.03%	550.03%

costs of the inputs and outputs of the flows found in each process. Lastly in the VP calculation, the availability and performance were both estimated to be 0.95.

The results presented in Table 3 show that, if a trailing suspension arm manufacturer adopts any of the policies, the gains in terms of generated value performance are small, with the highest gains being provided by the adoption of both policies. However, when taking into consideration the *eco-efficiency* indicator, the manufacturer will benefit

Table 4
Eco-efficiency (with COI) of heating process 2 with machinery which consumes only electricity from wind turbines.

	Process	Current	1 - Renewable energy	2 - Recycled material	3 - Combination of 1 and 2
Environmental performance					
	Heating process 3	1.98E-11	1.92E-11	1.99E-11	1.85E-11
Value performance					
	Heating process 3	5.34	5.34	5.34	5.34
Eco-efficiency (with COI)					
	Heating process 3	2.34E11	2.17E17	2.33E11	2.25E17
	Total (%)		9.27E7%	99.57%	9.62E7%

the most when adopting both policies, as illustrated in Fig. 3. This benefit is the result of slight gains in terms of generated value, but the biggest gains derive from the drastic reduction in generated emissions and especially the reduction of generated CO_2 emissions.

Furthermore, the eco-efficiency results indicate that the adoption of solely renewable energy could approach a sustainability level close to the ideal scenario. This is in contrast to the glass bottle manufacturer use case, where it was necessary to adopt both policies to achieve high sustainability (Figs. 2 and 3).

Next, the COI was estimated in a scenario where the machinery used in heating process 2 would be powered by renewable energy sources and not fossil fuels (Table 4).

The COI introduction in the calculations for eco-efficiency has a significant impact on the result. This is expected since the *setup* and *downtime costs* would be high for replacing the equipment in the heating process 2 with equipment powered by the national electric grid and in particular its part of renewable energy sources. In greater detail, the *setup cost* was estimated at €500,000, while the *downtime cost* was estimated at €400,000. Moreover, it was assumed that there are no changes required in the manufacturer infrastructure to consume energy from renewable energy sources, but it is supplied directly from the national power grid.

Hence, based on the results presented in Table 4, the best approach to improve its sustainability is by adopting both circular economy strategies. This is because the COI, when calculating the eco-efficiency for

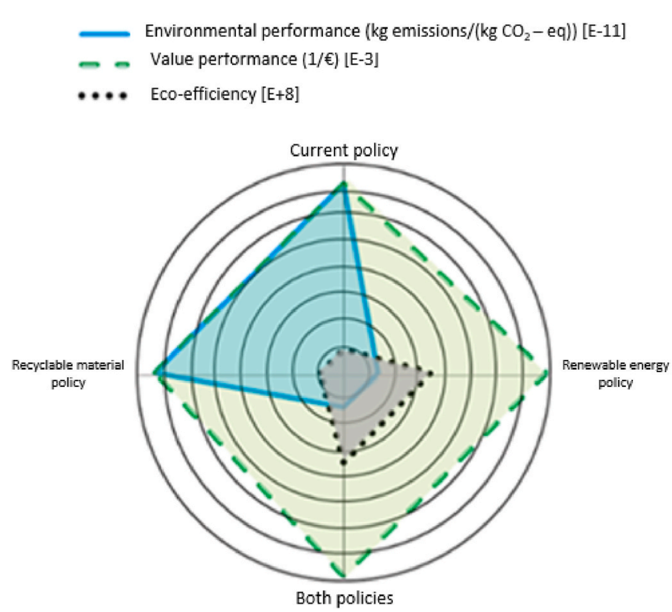

Fig. 3. Performance illustration for alternative circular economy strategies in trailing suspension arm manufacturing.

policies 1 and 3, remains the same, in the specific use case, which means that the results do not differ from the findings when COI is not calculated. Thus, as was the case in the scenario where COI was not considered, the most suitable strategy for achieving green manufacturing is the adoption of both renewable energy and recycled material. However, the results may differ in use cases where the equipment required in a manufacturing process differs based on the adopted sustainable manufacturing policy.

5. Conclusions

This work discusses an extended *eco-efficiency* indicator using the LCA and LCC, and linking them to product quality, process performance, and availability. Moreover, while the extended *eco-efficiency* indicator targets single processes, by combining all processes of a manufacturing system, the extended indicator can be calculated on a system level. The proposed methodology has been evaluated in two industrial pilot cases, with real-world data, with the extended *eco-efficiency* indicator providing meaningful insights into both the environmental and value performance. Both use cases, through the proposed methodology, are expected to better conform to the reduce principle of circular economy. Specifically, they are expected to gain insight into the processes that require intervention to reduce the quantity of resources and raw materials to manufacture the same product or part with the same quality. Also, assuming similar use cases, the insight provided by the extended eco-efficiency indicator could also refer to the recover principle, with the indication of processes where material or energy could be recovered and reused. This in turn allows an impact assessment, at a high level, for making a transition to a circular economy strategy in terms of environmental and value performance as well as in terms of capital investment required.

Although the environmental and cost data required by the indicator are usually available in the industry, there are still limitations as the data must be accurate enough and, in some cases, such as in the case of small and medium-sized enterprises, the availability of dedicated hardware and software to collect the necessary data is limited.

The proposed methodology has been evaluated in two industrial use cases in order to affirm its general applicability aspect. Nevertheless, testing the proposed methodology in more industrial use cases is a necessary next step. However, the methodology is limited by the boundaries set during the creation of the process-level, and its extension system-level, LCA model based on ISO 14044:2006. This is also applicable to the construction of the process-level LCC model.

To check the reproducibility of the proposed methodology, the extended eco-efficiency indicator was used to quantify the impact of adopting a circular economy strategy in two different industrial use cases. Furthermore, in the context of reproducibility, the methodology was successfully tested from the perspective of the two industrial use cases and the results coincided with the initially obtained results. However, the results presented in section 4, cannot be fully replicated by a third party without access to similar LCA models, and production lines to obtain similar real-world data as the ones used in section 4.

Future research will seek to evaluate and validate the proposed method in more cases in order to enhance its robustness. Future research will also target the use of the extended *eco-efficiency* indicator in simulation environments where it could be used to evaluate alternative what-if scenarios in terms of sustainability and green manufacturing. We also seek to consider feedback loops that will use the outcome of the indicator for adjusting process parameters in manufacturing systems to improve their performance and enhance their sustainability through the reduction of waste. Lastly, future research will focus on integrating into the methodology a temporal horizon parameter to capture the importance that a transition to a circular economy strategy should be gradual in order for the improvements to the environmental performance of a manufacturing process or system to not hinder its value performance.

Nevertheless, the proposed indicator allows a comparison against alternative circular economy strategies, allowing the creation of more sustainable business models for manufacturers, by assessing at the same time both the technical and financial aspects of their production processes. This is justified by the study's findings since both use cases are expected to better conform to the reduce principle of circular economy and in relevant use cases, to the recover principle. Additionally, through the proposed indicator the significance of the relationship between economic and environmental sustainability is affirmed and the often not quantified aspect of mandatory equipment change in the process of transitioning to green manufacturing practices is highlighted.

Availability of data

The data that support the findings of this study are available on request from the corresponding author, K.A. The data are not publicly available due to confidentiality restrictions.

CRediT authorship contribution statement

Nikolaos Nikolakis: Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Paolo Catti:** Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Alexis Chaloulos:** Writing – original draft, Software, Methodology, Investigation. **Wilhelm van de Kamp:** Writing – original draft, Validation, Data curation. **Mildred Puerto Coy:** Writing – original draft, Validation, Resources, Data curation. **Kosmas Alexopoulos:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

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.

Data availability

Data will be made available on request.

Acknowledgements

This work was partially supported by the HORIZON-CL4-2021-TWIN-TRANSITION-01 openZDM project, under Grant Agreement No. 101058673. The paper reflects the authors' views, and the Commission is not responsible for any use that may be made of the information it contains.

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