

Circular economy in the manufacturing sector as enabler of sustainable manufacturing

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Abstract: The role of manufacturers for our society is gaining importance more and more, and currently the manufacturing sector is considered one of the most polluting and resource greedy sectors. The inefficiencies registered in manufacturing boost the uncontrollable rise of resources consumption and the rise of CO₂ emissions, which nowadays represent two of the major problems affecting the society. To tackle these issues, policymakers have promoted the sustainable developed goals (SDG) and, both industry and scientific literature have started to investigate the potentialities of sustainable manufacturing to address this goals. More recently the attention has been moved over a new economy, called “circular economy” (CE). This paradigm, characterised by specific principles, aims to design systems allowing the regeneration and restoration of resources. The present work aims to elucidate how CE paradigm operates as driver of sustainable manufacturing through the adoption by manufacturers of different CE strategies. Indeed, this contribution presents how the CE principles have been translated in the manufacturing context through specific strategies, by highlighting their economic, environmental and social potentialities to embrace the SDGs. Understanding what are the applicable CE strategies and their sustainable potentialities would facilitate the transition towards circular industries by making manufacturers more aware of the possible paths to be undertaken. This paper is based on a literature review, grounded on English-written documents available on Scopus and Web of Science. Moreover, this review, on the basis of the scientific literature gaps, paves the way for future research directions.

Keywords: Literature review, Circular Economy, Circular Manufacturing, Sustainability, Manufacturing

1. Introduction

The manufacturing sector has been always considered an economic engine for our society and, today more than ever, its role is increasingly gaining importance (McKinsey Global Institute and McKinsey Operations Practice, 2012). Although the positive impact on the economy of countries worldwide, this sector impacts a lot on the pollution generation, through CO₂ emissions, and the uncontrollable resources consumption too, which negatively affects environmental, economic and social aspects. For these reasons, it is required to promote more sustainable strategies for sustainable development (McKinsey&Company, 2012). Therefore, policymakers through the *sustainable development goals (SDGs)* designed targets to be addressed by the society and especially by manufacturers (United Nations, 2019). Indeed, all these actions aim to stimulate to think of new practices and methods to better exploit the planet resources.

In line with this trend, recently a new sustainable industrial economy, called “circular economy” (CE), arose, becoming one of the most promising sustainable strategies applicable by the entire society and exploitable by the manufacturing sector too (Geissdoerfer *et al.*, 2017). Furthermore, this economy is based on three pillars that concurrently enable to reduce resource consumption by limiting waste generation and providing a guideline for its future management too. In extant literature, the business

models designed for a CE transition of companies have been studied, even though the contextual factors influencing them are still an open point (Centobelli *et al.*, 2020). CE could support sustainability in manufacturing, however the exploration of the synergies that can be developed between SDGs targets and CE strategies have not investigated yet (Bhatt, Ghuman and Dhir, 2020), as well as the evaluation of the overall benefits that CE has on the sustainable pillars (Sassanelli *et al.*, 2019).

Therefore, the aim of the present work is to understand how CE paradigm operates as driver of sustainable manufacturing. Indeed, the present paper will present how the CE principles have been translated in the manufacturing context through specific CE strategies, by highlighting their economic, environmental and social potentialities to embrace the SDGs targets.

To address the paper objectives, the present work is structured as follows: (2) Methodology in which it is described the methodology used to develop the review characterizing the present work, (3) Research Context that creates the ground to address the general goal by defining both CE and sustainable manufacturing concepts, (4) The literature review results and discussion in which the descriptive statistics are reported, and it is presented how the CE is adopted in the manufacturing sector with the relative sustainable potentialities, (5) Conclusions in which

main findings, gaps, and future research directions are proposed.

2. Methodology

A two-stage literature review was performed to address the paper objective, that is to understand how CE operates as a driver for sustainable manufacturing by identifying the CE strategies adopted in the manufacturing sector, and to highlight their sustainable potentialities. The first step of the review, aiming at clearing out the link between CE and Sustainability, has been addressed through a review of the extant literature whose results are reported in section 3 to contextualise the research. This initial review was conducted on Scopus and Web of Science (WoS), the two major scientific search engines for industrial and management engineering, by searching in the abstract, title and keywords the following keywords: “Circular Economy” AND “Sustainability” AND “Manufacturing”. The contributions selected for the analysis were only reviews written in English, that are 19 papers. In addition, other 7 papers were included on the basis of the references of the paper selected and suggestions by experts.

The second step, reported in section 4, has been addressed by leveraging on a systematic literature review (SLR), which enables to systematically structure the scientific knowledge. Scopus and WoS were the search engines queried for this review by using the following keywords: (“circular economy” AND “manufacturing”) OR (“circular manufacturing”), to be searched in abstract, title and keywords. These keywords were identified after a first random screening of documents regarding these topics in both grey literature and scientific literature. The initial sample of papers accounted 742 contributions. The eligible criteria used are mainly three: articles and reviews published in journals and written in English. No-time frame was used to not bias the results, considering the quite old roots of CE and sustainability concepts. These eligibility criteria allowed to span appropriately the literature and to end up with 276 contributions, after having eliminated the duplicates coming from the two databases. To conclude, the final sample of papers selected for this review accounts 215 documents, since the last screening process, performed by reading first the abstract and then the entire paper, aimed at eliminating all the contributions out of scope of the research and thus, focused on chemical transformation processes and new materials development (20% of the entire amount of the contributions discarded), focused on organic cycles (28%) and last, contributions not focused on CE, but focused only on sustainability issues (52%).

Through the first step of this review, it was possible to create the ground and highlight the synergies among CE and sustainable manufacturing. While the SLR enabled to categorize the possible CE strategies adopted by manufacturers and to highlight their sustainable potentialities regarding the SDGs relying also on the first step findings. The CE strategies have been analyzed by using as analysis dimensions the environmental, economic and social, flanked by the SDGs covered by each strategy.

3. Research Context

This section lays the foundation to understand the context in which this research takes its roots, by investigating the concepts of sustainability and CE in manufacturing according to the extant literature.

3.1 Sustainable Manufacturing

Considering the undeniable need to boost sustainable development, in the '80s in the Brundtland Report the sustainable development concept was defined for the first time as “*The development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (WCED, 1987). It relies on three main principles: environmental, economic and social; also called the triple bottom line (TBL). This framework promotes not only companies' financial prosperity but also aims to push companies in taking care of people's well-being, without leveraging too much on planet resources exploitation (Elkington, 2013). Subsequently, the focus was moved from society and companies in general, to the manufacturing sector. The sustainable development concept shaped the roots for the sustainable manufacturing one, that is defined as “*the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life*” (Garetti and Taisch, 2012). Indeed, sustainable manufacturing aims to take advantage of the emerging technologies to optimize industrial processes and reduce inefficiencies. Thus, the ambition is to reduce resources consumption and pollution generation through manufacturing processes optimization and technological improvement. More recently, United Nation designed the SDGs that promote to address the TBL through seventeen urgent actions: 1) no poverty, 2) zero hunger, 3) good health and well-being, 4) quality education, 5) gender equality, 6) clean water and sanitation, 7) affordable and clean energy, 8) decent work and economic growth, 9) Industry innovation and infrastructure, 10) reduced inequalities, 11) sustainable cities and communities, 12) responsible consumption and production, 13) climate action, 14) life below water, 15) life on land, 16) peace, justice and strong institutions, 17) partnerships for the goals (United Nations, 2019).

3.2 Circular Economy

In the '90s arose the concept of CE that today is defined as an industrial economy “*regenerative and restorative by intention and design*” (The Ellen MacArthur Foundation, 2013). It is driven by three pillars: (i) preserve and enhance natural capital, (ii) optimize resource yields and (iii) foster systems effectiveness; that are fulfilled through either organic cycles or technical ones (The Ellen MacArthur Foundation, 2015). Indeed, this paradigm aims to eliminate toxic substances usage and to limit resources consumption, in respect of nature availability, by slowing, narrowing and closing the resources loop (Bocken, Miller and Evans, 2016), thus extending product life cycles. Moreover, this economy can be adopted at different levels, which are reflected in micro (i.e. consumers,

products and firms level), meso (i.e. network of industrial actors level) and macro (i.e. cities, regions and nations level) (Ghisellini, Cialani and Ulgiati, 2016). Considering the great potentialities of CE, policymakers too are promoting its adoption through new action plans (European Commission, 2020).

To conclude, CE could have potentialities in supporting sustainability, nevertheless before defining the CE strategy to be adopted is important to evaluate its sustainable performances (Kravchenko, Pigosso and McAloone, 2019), and it is still not present in the literature the overall evaluation of CE benefits affecting the different sustainable pillars (Sassanelli *et al.*, 2019) and the synergies with the SDGs (Bhatt, Ghuman and Dhir, 2020).

4. Literature review results and discussion

4.1 Descriptive Statistics

The SLR enabled to provide some statistics over the papers selected for this review. First, the contributions were analysed considering the sustainable pillars addressed. In **Fig.1** are reported the percentages covered by the sample of papers. As the graph shows, most of them are focused on environmental aspects while social issues are neglected in many studies.

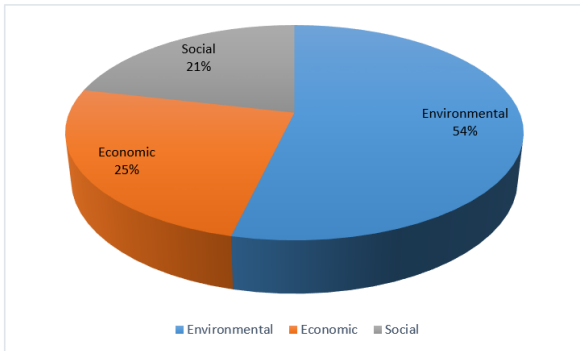


Figure 1: TBL addressed by the sample of papers

Second, it has been investigated the amount of papers dealing with a certain CE strategy in order to evaluate the most diffused in the scientific literature. The results are reported in **Fig.2**. The closed-loop supply chain is the most diffused one. This result is justified by the fact that this strategy is the one that enables resource circularity among industrial actors (Govindan, Soleimani and Kannan, 2015). Indeed, this value is immediately followed by reuse, remanufacture and recycling strategy which are adopted in the closed-loop supply chains.

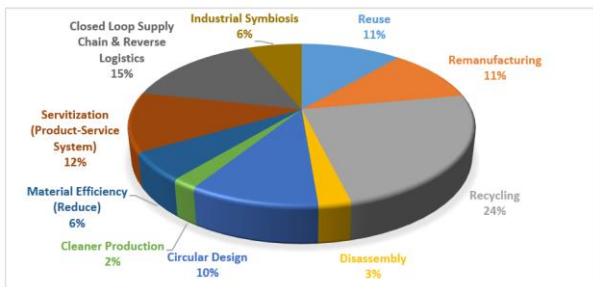


Figure 2: CE strategies adopted by manufacturers

4.2 Circular economy adoption by manufacturers

The **Table 1** reports the classification of CE strategies adopted in the manufacturing sector analysed through the TBL framework and the SDGs. In particular, in **Table 1**, for each strategy is given the definition gathered from the extant scientific literature, and for each strategy are analysed the potentialities in fostering the environmental, social or economic sustainability while closing the resources loops by highlighting the SDGs addressed.

The common ground of the CE strategies emerged from the SLR is the willingness to design circular systems and to put in place actions enabling to close resource loops, in order to limit excessive resources consumption and waste generation. Indeed, each CE strategy fosters sustainable development by relying on a specific approach to pursue this objective in line with the CE pillars. Furthermore, these strategies are adoptable at different stages of the product life cycle, and they might require the intervention of more than one actor as in the case of industrial symbiosis and closed-loop supply chain, according to the scale of adoption level. Among the possible strategies, one of the most important is the adoption of circular design, which is conceived for designing the product to embrace CE pillars, thus by enabling its circularity (den Hollander, Bakker and Hultink, 2017). This stage owns the majority of the potentialities to make resources recirculate once they have been used, since it represents the basis for the adoption of end-of-life CE strategies, such as remanufacturing (Sitcharangsie, Ijomah and Wong, 2019), recycling (Zhong and Pearce, 2018) and reuse (Liu *et al.*, 2018), that all enable to respect circular pillars even when the product has no more value from the user perspective. Indeed, these strategies aim to regenerate value from the product once used and make it undertake a new life cycle. Detrimental for the adoption of these strategies, is the possibility to disassemble the product (Favi *et al.*, 2019; Marconi *et al.*, 2019) that, indeed as to be considered in the design phase. Once products have been sold, during the usage phase, these are no more under the control of the producer, and in order to enable the respectfulness of the CE pillars, strategies like servitization are applied by manufacturers (Bocken *et al.*, 2017). Indeed, these enable to provide the right services and supports to the users, to extend the product life cycle. Moreover, in order to enable the internal respectfulness of CE principles, traditional processes of manufacturing companies must be revised. For instance, by adopting cleaner production processes (Sousa-Zomer *et al.*, 2018), reduce material and energy consumption (Choi, Thangamani and Kissock, 2019) and, in case it is required, to adopt appropriate measures to manage the waste generated (Rapsikevičienė, Gurauskienė and Jučienė, 2019). In some cases, CE pillars can be fulfilled thanks to the intervention of more than one industrial actors as in the case of closed-loop supply chains (Lapko *et al.*, 2019), where usually the reverse logistic network is designed to make product turned back, or industrial symbiosis (Domenech *et al.*, 2019), where resources are exchanged also among actors not belonging to the same supply-chain.

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Table 1: CE strategies applied in the manufacturing sector together with sustainable potentialities

| CE Strategy | Definition | Sustainable Development Goals | Sustainable Pillars Potentially Covered |
|--------------------|---|---|---|
| Reuse | This strategy, once analyzed the product status and condition, aims to plan and perform all the activities and processes enabling to reuse the product directly at the end of its life cycle (e.g. (Liu <i>et al.</i> , 2018)) | <ul style="list-style-type: none"> • SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) | <ul style="list-style-type: none"> • <i>Environmental</i>: it enables to reduce resource consumption by reusing the original product without adding new resources. • <i>Social</i>: it enables to create a second-hand market satisfying the need of a wide number of customers with different financial incomes |
| Remanufacturing | This strategy aims to plan and perform all the activities and processes required to restore a used product in compliance with its original quality, specifications, performances, and warranty (e.g. (Sitcharangsie, Ijomah and Wong, 2019)) | <ul style="list-style-type: none"> • SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) | <ul style="list-style-type: none"> • <i>Environmental</i>: it enables to reduce resource consumption by limiting only to those required • <i>Economic</i>: it enables to limit costs to produce new products by undertaking only part of the manufacturing process activities |
| Recycling | This strategy, through chemical and physical transformation processes, aims to reuse the components or materials by reducing resources consumption and pollution generation (e.g. (Zhong and Pearce, 2018)) | <ul style="list-style-type: none"> • SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) | <ul style="list-style-type: none"> • <i>Environmental</i>: it enables to reduce resource consumption thanks to physical and chemical transformation processes of already used resources to reintroduce them into new cycles |
| Disassembly | This strategy aims to define and perform all the activities and processes to disassemble in sub-components and materials the product and, under CE perspective, this strategy enables to easily recycle or reuse the single parts (e.g. (Favi <i>et al.</i> , 2019; Marconi <i>et al.</i> , 2019)) | <ul style="list-style-type: none"> • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) | <ul style="list-style-type: none"> • <i>Environmental</i>: it enables to substitute only selected components and thus, to limit resources consumption for the production of totally new products • <i>Economic</i>: it enables to substitute only selected components and thus, to limit expenses for the production of totally new products by purchasing only necessary components • <i>Social</i>: It enables to keep the product updated and renewed by the user himself |
| Circular Design | This strategy aims to plan and perform all the activities to be done at the design phase of the product life cycle in order to prevent excessive resource consumption. This strategy eases end-of-life circular practices such as disassembly and thus, recycling, reuse and remanufacturing (e.g. (den Hollander, Bakker and Hultink, 2017)) | <ul style="list-style-type: none"> • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) | <ul style="list-style-type: none"> • <i>Environmental</i>: It enables to design products by limiting resource usage and extending the product life cycle • <i>Social</i>: It enables to meet customer needs while respecting circular economy pillars |
| Cleaner Production | This strategy, being based on product optimization, input substitution and sharing of renewable and recyclable resources, enables to limit resources consumption and toxic substances used in the production processes (e.g. (Sousa-Zomer <i>et al.</i> , 2018)) | <ul style="list-style-type: none"> • SDG 6 (Clean water and sanitation) • SDG7 (Affordable and clean energy) • SDG9 (Industry innovation and infrastructure) • SDG11 (Sustainable cities and communities) | <ul style="list-style-type: none"> • <i>Environmental</i>: it aims to reduce toxic substances usage and thus, their dispersion in the air • <i>Social</i>: it reduces negative implications on human health • <i>Economic</i>: by optimizing processes it reduces resources purchasing costs |

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|--|--|---|--|
| Material Efficiency (Reduce) | This strategy aims to plan and perform all the activities and processes to optimize material used along the production process and product usage (e.g. (Choi, Thangamani and Kissock, 2019)) | <ul style="list-style-type: none"> • SDG12 (Responsible production and consumption) • SDG13 (Climate action) • SDG14 (Life below water) • SDG15 (Life and land) • SDG 6 (Clean water and sanitation) • SDG9 (Industry innovation and infrastructure) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) • SDG13 (Climate action) • SDG14 (Life below water) • SDG15 (Life and land) | <ul style="list-style-type: none"> • <i>Environmental:</i> It enables to reduce material consumption both during the design phase but also during the usage phase • <i>Economic:</i> It enables to reduce material consumption both during the design phase but also during the usage phase that implies to limit the expenses |
| Waste Management | This strategy corresponds to all the activities and processes required to dismantle waste generated by manufacturers by also handling hazardous waste (e.g. (Rapsikevičienė, Gorauskienė and Jučienė, 2019)) | <ul style="list-style-type: none"> • SDG 6 (Clean water and sanitation) • SDG9 (Industry innovation and infrastructure) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) • SDG13 (Climate action) • SDG14 (Life below water) • SDG15 (Life and land) | <ul style="list-style-type: none"> • <i>Social:</i> it enables to limit negative implications for human health • <i>Environmental:</i> it aims to limit pollution generation and toxic emissions |
| Servitization (Product-Service system) | This strategy aims to plan and perform all the activities and processes to sell a service by using a product as a means. It uses both tangibles (products) and intangibles (services) to satisfy final customers' needs by limiting resources consumption (e.g. (Bocken <i>et al.</i> , 2017)) | <ul style="list-style-type: none"> • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) • SDG17 (Partnerships for the goal) | <ul style="list-style-type: none"> • <i>Environmental:</i> it limits resource consumption through product life cycle extension • <i>Social:</i> it enables to address customer needs in a more personalized way |
| Closed-loop supply chain/ Reverse Logistics | This strategy aims to plan and perform all the activities to establish reverse flows of resources along the supply chain (e.g. (Lapko <i>et al.</i> , 2019)) | <ul style="list-style-type: none"> • SDG11 (Sustainable cities and communities) • SDG17 (Partnerships for the goal) | <ul style="list-style-type: none"> • <i>Environmental:</i> it enables to establish reverse flows of resources to consume less resource as a total along the entire supply chain • <i>Economic:</i> through the reverse flow of resources it is possible to limit the purchase of new resources • <i>Social:</i> it is possible to combine different stakeholders needs by respecting circular economy pillars |
| Industrial Symbiosis/ Industrial Eco-Parks | This strategy refers to the physical exchange of resources as materials, energy, and by-products among industrial actors that do not belong to the same supply chain (e.g. (Domenech <i>et al.</i> , 2019)) | <ul style="list-style-type: none"> • SDG11 (Sustainable cities and communities) • SDG17 (Partnerships for the goal) | <ul style="list-style-type: none"> • <i>Environmental:</i> it enables to limit waste production • <i>Economic:</i> it enables to not discard by-products and waste by converting them into new possible revenue sources |

Each CE strategy has great potentialities in covering at least one of the sustainable pillars and has specific characteristics which enable to address the SDGs (see **Table 1**). Indeed, to implement sustainable development and apply CE strategies the preliminary target is to encounter what is proposed by United Nations.

Looking at *reuse*, this strategy unveils potentialities in addressing the SDG1 by enabling the creation of a second-hand market which indirectly covers the SDG8, whose inherent goal is to reduce the unemployment rate worldwide. The same outcomes are perceived also for *remanufacturing* and *recycling* strategies that not only sustain the development of a second-hand market, but in addition they cover also the SDG12 by promoting a responsible production and consumption. This is true also for *disassembling* since it enables the adoption of the above mentioned strategies. As a consequence, considering that these strategies are enabled thanks to an adequate product design, *circular design* strategy covers the SDG12 as well, especially by promoting a responsible consumption by designing product whose characteristics address the CE pillars. Since new businesses could arise through *circular design*, this strategy covers as well the SDG8. *Servitization* strategy addresses exactly the same goals of *circular design* because of shared reasons. Therefore, it promotes as well the rising of new businesses and thus, new opportunities to reduce the unemployment rate; and as well of circular design, it supports a responsible consumption, since it provides customised services enhancing the CE pillars without neglecting customers' needs. The SDGs 6, 9, 12, 13, 14 and 15 are covered by *cleaner production*, *resource efficiency* and *waste management*, since they are all based on the idea to promote the appropriate usage of resources through adequate innovative infrastructures whenever possible. This has a direct effect on the increase of responsible production and an indirect effect on the pollution generation and thus, on water and land resources conditions. In particular, by eliminating hazardous waste it is possible to encounter the inherent target of improving water quality of the SDG6, and as lateral consequences also the SDG 13, 14 and 15 are addressed. Moreover, *cleaner production* aims to promote the usage of sustainable energy resources during the production processes and for this reason it covers also the SDG7. The SDG17 is highly supported by those strategies which aim to make collaborate different actors, such as the *industrial symbiosis* strategy and *closed-loop supply chain*. Actually, also the servitization strategy is aligned with this goal even though the collaboration in this case is set up with the end-user. To conclude, the above mentioned strategies all contribute to the SDG11 since if concurrently adopted, these CE strategies could improve also the sustainability of cities and communities.

5. Conclusions

The present work, through a SLR, enabled to identify the CE strategies applicable by manufacturers, by defining how these strategies operate as enabler of sustainable manufacturing and support the embracement of the SDGs. Therefore, the CE strategies are analysed to envisage what are their potentialities in terms of social,

environmental and economic development in embracing the SDGs. CE strategies, applicable at different scales (i.e. micro, meso and macro) coherently with the SDGs, enable to fulfil the sustainable pillars by closing the resources loops. For this reason they might be considered as subsets of sustainable manufacturing ones, with embedded the ability to enable the refurbishment of resources. According to this qualitative analysis emerged that, even though the CE pillars are much more focused on environmental and social aspects, the economic pillar emerged to be quite diffused in the extant literature at the expense of the social one. Indeed, this is a little bit neglected, while dealing with manufacturers since they are driven by economic benefits. This consideration is aligned with the SDGs covered by the CE strategies. The strategies identified present a limited attention over to more social oriented SDGs such as the SDG2 (Zero Hunger), SDG3 (Good Health and well-being), SDG4 (Quality education) and SDG5 (Gender equality). In future researches, further investigation about these issues from the manufacturing sector perspective should be conducted. Manufacturing companies should promote gender equality and sustain high quality education level inside their plants and, could promote and support researches addressing the SDG2 and SDG3.

In future researches, a quantitative model assessing the potentialities of the CE strategies in embracing the SDGs should be developed. This would create more awareness among practitioners and would make them better understand the benefits generated through the adoption of these strategies in promoting sustainable development.

Last, this review unveiled that the CE strategies applied in manufacturing would better support the SDGs through industry innovation that is eased by the usage of technologies. Therefore, this other research stream should be further investigated, to understand what are the main criticalities, and what might be the possible enablers for manufacturers from a technological view-point.

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