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 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 and related benefits. 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 affect environmental, economic and social aspects. For these reasons, it is required to promote more sustainable strategies to promote sustainable manufacturing (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, 2015). As a consequence, 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 paradigms 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, this contribution will elucidate 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 total. 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 in general (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 analysed by using as analysis dimensions the environmental, economic and social, flanked by the SGDs 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 thought 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, 2015).

3.2 Circular Economy

CE is defined as an industrial economy that is "*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 (The Ellen MacArthur Foundation, 2015). 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 into 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). Therefore, 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 Figure 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.

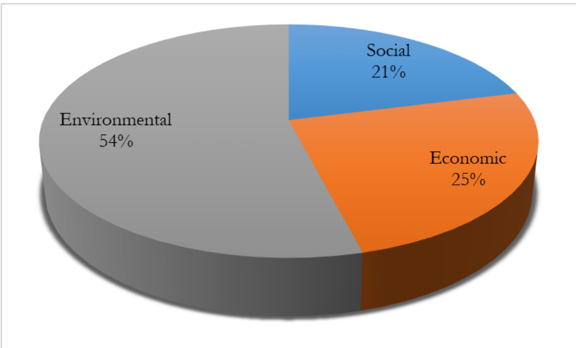

Figure 1: TBL addressed by the sample of papers

Second, it has been investigated the amount of papers dealing with each CE strategy to evaluate their diffusion in the scientific literature (see Figure 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, it is immediately followed by reuse, remanufacture and recycling strategies which are necessary in closed-loop supply chains.

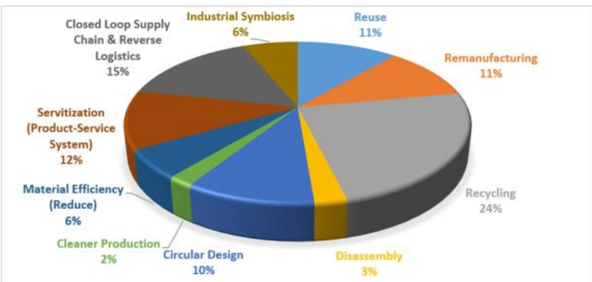

Figure 2: CE strategies adopted by manufacturers

4.2 Circular economy adoption by manufacturers

Table 1 reports the classification of CE strategies adopted in the manufacturing sector analysed through the TBL framework and the SDGs, to identify CE strategies sustainable potentialities while closing the resources loops.

The common ground of all the CE strategies, that 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, 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 product resources circularity (den Hollander, Bakker and Hultink, 2017). The design 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). Indeed, these three strategies can be implemented at the end of product lifecycle, to ensure product and product resources reintroduction in subsequent life cycles even when the product has no more value from the user perspective. These strategies aim to regenerate products or products components and materials in order to retain as much value as possible once the product has been used. Detrimental for the adoption of these strategies is the possibility to disassemble the product (Favi *et al.*, 2019; Marconi *et al.*, 2019) whose characteristic require to be considered in the design phase too. Once products have been sold, during the usage phase, these are no more under the control of the producer, and to enable the respectfulness of the CE pillars, strategies like servitization are applied by manufacturers (Bocken *et al.*, 2017). Indeed, these enable to provide appropriate services and supports to the users, to extend the product lifecycle. 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), by reducing material and energy consumption (Choi, Thangamani and Kissock, 2019) and, in case it is required, by adopting 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 to create sustainable synergies.
Therefore, each CE strategy, in different stages of the product lifecycle, has great potentialities in covering at least one of the sustainable pillars and has specific characteristics which enable to address part of the SDGs (see Table 1). *Reuse* strategy unveils potentialities in addressing the SDG1 by enabling the creation of a second-hand market.

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 analysed 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 *et al.*, 2018))	• SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities)	• *Environmental*: it enables to reduce resource consumption by reusing the original product without adding new resources. • *Social*: 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))	• SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption)	• *Environmental*: it enables to reduce resource consumption by limiting only to those required • *Economic*: 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))	• SDG1 (No poverty) • SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption)	• *Environmental*: 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 *et al.*, 2019; Marconi *et al.*, 2019))	• SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption)	• *Environmental*: it enables to substitute only selected components and thus, to limit resources consumption for the production of totally new products • *Economic*: it enables to substitute only selected components and thus, to limit expenses for the production of totally new products by purchasing only necessary components • *Social*: 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))	• SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption)	• *Environmental*: It enables to design products by limiting resource usage and extending the product life cycle • *Social*: 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 *et al.*, 2018))	• SDG 6 (Clean water and sanitation) • SDG7 (Affordable and clean energy) • 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)	• *Environmental:* it aims to reduce toxic substances usage and thus, their dispersion in the air • *Social*: it reduces negative implications on human health • *Economic*: by optimizing processes it reduces resources purchasing costs

Resource Efficiency (Reduce)	This strategy aims to plan and perform all the activities and processes to optimize material and energy used along the production process and product usage (e.g. (Choi, Thangamani and Kissock, 2019))	• SDG 6 (Clean water and sanitation) • SDG7 (Affordable and clean energy) • 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)	• *Environmental*: It enables to reduce resource consumption both during the design phase but also during the usage phase • *Economic*: It enables to reduce resource 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, Gurauskienė and Jučienė, 2019))	• 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)	• *Social*: it enables to limit negative implications for human health • *Environmental*: 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 *et al.*, 2017))	• SDG8 (Decent work and economic growth) • SDG11 (Sustainable cities and communities) • SDG12 (Responsible production and consumption) • SDG17 (Partnerships for the goal)	• *Environmental*: it limits resource consumption through product life cycle extension • *Social*: 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 *et al.*, 2019))	• SDG9 (Industry innovation and infrastructure) • SDG11 (Sustainable cities and communities) • SDG17 (Partnerships for the goal)	• *Environmental*: it enables to establish reverse flows of resources to consume less resource as a total along the entire supply chain • *Economic*: through the reverse flow of resources it is possible to limit the purchase of new resources • *Social*: 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 *et al.*, 2019))	• SDG9 (Industry innovation and infrastructure) • SDG11 (Sustainable cities and communities) • SDG17 (Partnerships for the goal)	• *Environmental*: it enables to limit waste production • *Economic*: it enables to not discard by-products and waste by converting them into new possible revenue sources

This 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 they cover also the SDG12 by promoting a responsible production and consumption, since they aim to regenerate resources by limiting the introduction of new resources as inputs in the system. 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 the implementation of innovative processes by fostering industrial innovation. This has a direct effect on the increase of responsible production and an indirect effect on the pollution generation 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* and *resource efficiency* aim both to promote the usage of sustainable energy resources during the production processes, and for this reason it covers also the SDG7. The SDG9 and SDG17 are highly supported by those strategies which aim to make collaborate different actors, such as the *industrial symbiosis* strategy and *closed-loop supply chain,* that inevitably require innovative infrastructures. Actually, the *servitization* strategy too is aligned with the SDG17, even though the collaboration in this case is set up with the end-user. To conclude, all the above mentioned strategies contribute to the SDG11 since, if concurrently adopted, they could enhance cities and communities' sustainability.

5.Conclusions

The present work, through a SLR, enabled to clarify the synergies among CE and the SDGs by defining how CE strategies operate as enabler of sustainable manufacturing in embracing the SDGs. CE strategies, that are 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, CE strategies might be considered a subset of sustainable manufacturing strategies, with embedded the ability to enable the refurbishment of resources. This qualitative analysis unveiled that, even though the CE pillars are 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, manufacturers are often primarily driven by economic benefits. This consideration is aligned with the SDGs covered by the CE strategies, since they present a limited attention over to the more social oriented SDGs, such as the SDG2 (Zero Hunger), SDG3 (Good Health and well-being), SDG4 (Quality education) and SDG5 (Gender equality). This result requires to be further validated through practitioners' interviews or case studies to gather empirical evidences. Nevertheless, further investigation about how manufacturing companies could promote gender equality and sustain high quality education level inside their plants should be conducted, backed by researches on how they could promote and address projects covering the SDG2 and SGD3.

In addition, 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 it 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 in the end 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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