Circular Economy and Sustainability

Giovanni Lagioia · Annarita Paiano ·
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Innovation, Quality and Sustainability for a Resilient Circular Economy

The Role of Commodity Science, Volume 1

Springer

Circular Economy and Sustainability

This book series aims at exploring the rising field of Circular Economy (CE) which is rapidly gaining interest and merit from scholars, decision makers and practitioners as the global economic model to decouple economic growth and development from the consumption of finite natural resources. This field suggests that global sustainability can be achieved by adopting a set of CE principles and strategies such as design out waste, systems thinking, adoption of nature-based approaches, shift to renewable energy and materials, reclaim, retain, and restore the health of ecosystems, return recovered biological resources to the biosphere, remanufacture products or components, among others.

However, the increasing complexity of sustainability challenges has made traditional engineering, business models, economics and existing social approaches unable to successfully adopt such principles and strategies. In fact, the CE field is often viewed as a simple evolution of the concept of sustainability or as a revisiting of an old discussion on recycling and reuse of waste materials. However, a modern perception of CE at different levels (micro, meso, and macro) indicates that CE is rather a systemic tool to achieve sustainability and a new eco-effective approach of returning and maintaining waste in the production processes by closing the loop of materials. In this frame, CE and sustainability can be seen as a multidimensional concept based on a variety of scientific disciplines (e.g., engineering, economics, environmental sciences, social sciences). Nevertheless, the interconnections and synergies among the scientific disciplines have been rarely investigated in depth.

One significant goal of the book series is to study and highlight the growing theoretical links of CE and sustainability at different scales and levels, to investigate the synergies between the two concepts and to analyze and present its realization through strategies, policies, business models, entrepreneurship, financial instruments and technologies. Thus, the book series provides a new platform for CE and sustainability research and case studies and relevant scientific discussion towards new system-wide solutions.

Specific topics that fall within the scope of the series include, but are not limited to, studies that investigate the systemic, integrated approach of CE and sustainability across different levels and its expression and realization in different disciplines and fields such as business models, economics, consumer services and behaviour, the Internet of Things, product design, sustainable consumption & production, bio-economy, environmental accounting, industrial ecology, industrial symbiosis, resource recovery, ecosystem services, circular water economy, circular cities, nature-based solutions, waste management, renewable energy, circular materials, life cycle assessment, strong sustainability, and environmental education, among others.

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Contents

Part II Agriculture, Biomass, Foods and Beverages: Circular Economy and Sustainability

Chapter 55
Green Smart Manufacturing: Potentials and Limits Toward Industry 5.0

Raffaella Taddeo, Veronica Casolani, and Alberto Simboli

Abstract In recent decades, progressive industrial digitalization has provided companies with an increasing capability to improve the efficiency of processes and quality products. In the recent frameworks of Industry 4.0, the pursuit of greater efficiency in the use of material, energy, and human resources assumes increasing importance in achieving the three goals—environmental, economic, and social—of sustainability. Even if the issue is widely debated, the mechanisms by which these technologies are applied from a life-cycle perspective, how they interact with each other, and how they produce effects on sustainability remain to be explored. The article aims to contribute to filling this gap by investigating the role played by so-called *smart technologies* in the context of *green manufacturing*. The study, through a critical analysis of the most recent scientific literature, provides a systematization of the technologies and solutions in the various stages of an ideal product life cycle, highlighting their operating interactions and potential effects in terms of sustainability, toward the future paradigm of Industry 5.0.

Keywords Green manufacturing · Smart technologies · Digitalization · Industry 4.0 and 5.0 · Sustainability

55.1 Introduction

Manufacturing companies are currently experiencing an important phase of renewal. The drive toward innovation requires, on the one hand, to give their processes timeliness, operational flexibility, and adaptability and, on the other hand, to achieve greater environmental efficiency and, more generally, the well-being of workers,

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stakeholders, and society. The first of these trends can be summarized in the concept of "smart manufacturing," a form of production integrating manufacturing assets with ICT-based technologies (Kusiak 2017). The concept of "green manufacturing," often used as synonymous with clean manufacturing, environmentally conscious manufacturing, environmentally responsible manufacturing, sustainable manufacturing, or sustainable production (Sangwan and Mittal 2015), appeared in the literature from the early 1990s. It describes a systematic and integrated approach for reducing the environmental impact associated with the production of goods, optimizing the use and selection of resources and technologies, and improving the overall efficiency. Although the two fields of research (and innovation) have emerged separately, more recently, thanks to the intensive use of integration technologies, they have found great potential for interaction, leading to the development of the concept of "green smart manufacturing" (GSM) (Váncza et al. 2020). GSM has progressively found wide support from governments of many countries, and there has been a significant increase both in research activities and industrial applications. Even if the theme is widely debated, the mechanisms by which these technologies are applied from a life-cycle perspective and how they produce effects on the three dimensions of sustainability remain to be fully explored.

55.2 Theoretical Background

Recently, following pandemic events, the issue of business digitalization has become increasingly relevant; it is considered one of the events that most accelerated the adoption of emerging technologies by companies (Amankwah-Amoah et al. 2021). Digitalization, however, starts much earlier; it denotes the partial or total conversion of elements, activities of the organization, and their value chain through integrated digital platforms and emerging digital technologies such as mobile and visual connectivity, cloud computing, robotics, smartphones, artificial intelligence, blockchain, additive manufacturing, 3D printing, and the Internet of Things (IoT) (Soto-Acosta 2020).

In the literature, the concept of digitalization is increasingly associated with that of Industry 4.0 (Skender and Ilker 2019); the latter is, in fact, characterized by the widespread application of digital technologies in an interconnected way between the production and management departments and outside companies. Oztemel and Gursev (2018) recommend the following definition: "*Industry 4.0 is a manufacturing philosophy that includes modern automation systems with a certain level of autonomy, flexible and effective data exchanges that support the implementation of production technologies of next generation, innovation in design and more personal and more agile production, as well as customized products*". This definition clearly indicates the presence of automation implementations (Machine To Machine - M2M, Internet of Things - IoT) with autonomous decision-making skills (smart factories), effective data exchange (Enterprise Resource Planning - ERP, Cloud), innovation support, and the invention of future generation technologies (augmented reality), as

well as more personal use of data (mobile systems, big data). All those mentioned fall within the "enabling technologies" and represent the pillars of the so-called Fourth Industrial Revolution, which has already found more advanced forms of development, such as the Digital Factory, the Smart Factory, the Virtual Factory, and cloud manufacturing (Salierno et al. 2021). The integrated and joint use of these technologies, although they have already been known and applied for many years, is therefore gradually and radically transforming the entire industrial paradigm from the man–machine relationship to the manufacturing process to relationships with suppliers and customers in each stage of the supply chain and, more generally, with society and the environment (Rüßmann et al. 2015).

55.3 Methods

The study, through a critical analysis of the most recent scientific literature, provides a systematization of technologies and solutions in the various stages of an ideal product life cycle, highlighting their operating interactions and the potential effects in terms of economic, environmental, and social sustainability. Figure 55.1 summarizes the analytical model of the research. A combined search was carried out on the Scopus scientific database (Elsevier 2022) on the subject of Smart Manufacturing, with the following keywords: Green Manufacturing, Smart Technologies, Digitalization, Industry 4.0. After selection based on abstract analysis, 328 articles were recognized. They were used for the first phase of the study: identifying the smart technologies adopted in the various stages of the life cycle. On this basis, those articles were further selected (37), which dealt with the themes of smart manufacturing in relation to sustainability. They were subjected to a critical analysis to highlight possible interactions between the two issues.

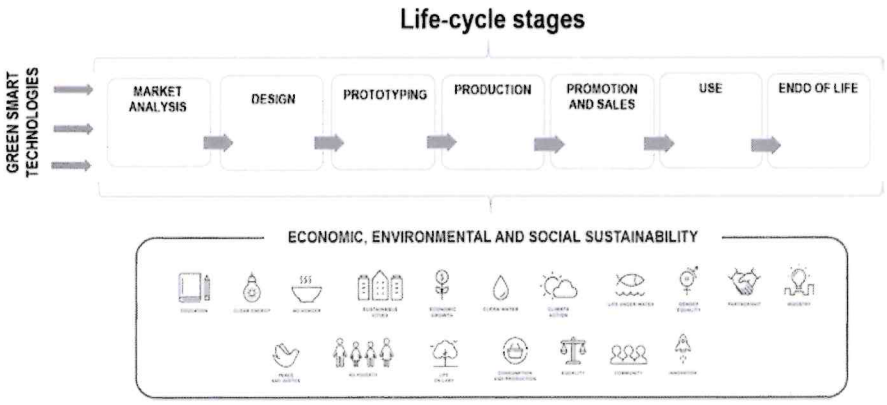

Fig. 55.1 The analytical model of the study

55.4 Results

Interesting results emerged from the analysis of the scientific literature, both in terms of the applicability and diffusion of smart technologies and their possible interactions with sustainability issues. They are described below.

55.4.1 Diffusion/Application of Smart Technologies

The analysis was conducted with a "life-cycle" perspective, aimed at representing the degree of applicability of the most widespread smart technologies in their various stages: market analysis, design, prototyping, production, sale, use, and end-of-life. Table 55.1 summarizes what emerged from the literature.

It can be noted how the degree of applicability of smart technologies is now very high; all phases of the life cycle are affected, but above all, there are increasingly significant spaces for synergistic interaction (standardization of languages, sharing of data, controls, and feedback in real-time), with potential logistical-production advantages and in relations with the end customer. It is also interesting to note how some of them are increasingly destined to play the role of integration technologies (e.g., IoT and big data analytics). In particular, it is noted that future studies could identify strategies to increase competitiveness through the combined use of enabling technologies of Industry 4.0 (Cricelli and Strazzullo 2021).

55.4.2 Smart Technologies and Sustainability

Many studies have revealed that digitalization can help achieve the 17 Sustainable Development Goals, divided into (1) economic, (2) environmental, and (3) social dimensions. From the analysis of the literature, it clearly emerges that these technologies can have a positive impact on (1) business profitability through material flow optimization, time-to-market reduction, space optimization, efficient use of resources, waste reduction, and lower inventory costs (Kayikci 2018). The use of artificial intelligence and data analytics can also offer customized professional development schemes or learning programs based on employee experience (Joshi et al. 2018). It is also widely accepted that digitalization can facilitate the transition toward (2) a circular economy. In fact, it allows the development of more efficient processes (reducing the use of resources and emissions) and, at the same time, provides transparent access to production and use/consumption data (e.g., monitoring and control systems in real time). In this direction, Cagno et al. (2021) use the ReSOLVE framework, which proposes six areas of action for the implementation of the circular economy: regenerate, share, optimize, loop, virtualize, and exchange. Vishnevsky et al. (2021) affirm that an additional positive environmental effect of

Table 55.1 Application of smart technologies in the life-cycle stages

Smart technologies		Life-cycle stages						
Name	Description	Marketing	Design	Prototyping	Production	Sale	Use	End of life
Internet of things	Network of devices that contain electronics, software, actuators, and connectivity that allows these objects to connect, interact and exchange data	X		X	X		X	
Big data analytics	Use of analytical tools in order to manage the flow of data and transform it into a productive and usable source of information	X			X	X		
Artificial intelligence	Field of knowledge that consists in placing computers/ machines in the position to acquire the ability to perceive and process input information, in order to perform in a similar way to human intelligence					X		X

(continued)

Table 55.1 (continued)

Smart technologies		Life-cycle stages						
Name	Description	Marketing	Design	Prototyping	Production	Sale	Use	End of life
Cloud computing	Technology that allows to use, via remote server, software and hardware resources (such as mass memories for data storage)	X						X
CAD	Software technology to support technical drawing and design		X					
Virtual reality	Computer-generated interactive experience that takes place within a simulated environment		X		X	X		
Augmented reality	Use of smart devices that add some virtual elements to the physical reality, in multimedia format		X					X
Simulation	Integration of IT tools aimed at the virtual reproduction of all aspects of a system with the aim of reprocessing data and improving decision-making							X

(continued)

Table 55.1 (continued)

Smart technologies		Life-cycle stages						
Name	Description	Marketing	Design	Prototyping	Production	Sale	Use	End of life
CAE	Computer software for simulating the performance of a product, component, or material			X				
Additive manufacturing	A manufacturing method capable of creating a physical object by printing layer by layer from a three-dimensional digital design or model			X	X			X
Autonomous robot	Autonomous, flexible, communicative, and cooperative industrial robots				X			X
Digital twin	Digital replication of physical assets, processes, systems, and devices				X			
Blockchain	Shared and immutable register that facilitates the transaction registration process and the traceability of assets in a commercial network						X	

digitalization is dematerialization. Moreover, (3) one of the essential indicators for assessing the social sustainability of production technologies concerns working conditions. The changing work environment and the integration of ICT in Industry 4.0 show some potential for the creation of sustainable value in the social dimension (Stock 2018). Possible benefits can be expected for better employee integration and inclusion, job enrichment, more effective worker education, and better work-life balance. Negative impacts could occur in terms of job replacement or simplification and in terms of controllability and complete transparency of work by those who could lead to the exploitation and extortion of employee performance.

55.5 Discussion and Conclusions: Toward Industry 5.0

From the analysis conducted, it clearly emerges that the possible areas of interaction of digital technologies in the field of GSM are multiple and operate "vertically," that is, in terms of greater material-energy efficiency of the production phases in which they are implemented, and "horizontally", as integration technologies, to support the collection, analysis, and sharing of data on the basis of a process, company and/or supply chain, improving company performance in terms of economic, environmental and social sustainability. These operational potentials find full integration in the future paradigm of Industry 5.0. (Lu 2021). To give a precise overview of Industry 5.0, the European Commission (2021) published a report entitled *Industry 5.0. Toward a sustainable, human-centric and resilient European industry*, it recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the well-being of the industrial worker at the center of the production process. The report explains how Industry 5.0 complements the existing Industry 4.0 paradigm, highlighting research and innovation as driving factors for the transition to a sustainable, human-centered, and resilient European industry. Industry 5.0 shifts the focus from shareholder value to stakeholder value, with benefits for all stakeholders, attempts to capture the value of new technologies by providing prosperity beyond employment and growth, respecting the borders of our planet, and places the well-being of the worker at the center of the production process. Industry 5.0 will also be characterized by an expanded vision, going beyond the for-profit production of goods and services. This broader scope constitutes three fundamental elements: human centrality, sustainability, and resilience. *Human centrality* includes responsible innovation, which places basic human needs and interests at the heart of the manufacturing process. It is necessary to ensure that the use of new technologies does not undermine the fundamental rights of workers, such as the right to privacy, autonomy, and human dignity. *Sustainability* means reducing energy consumption and greenhouse gas emissions, avoiding the depletion and degradation of natural resources, and guaranteeing the needs of future generations. *Resilience* refers to the need to develop a greater degree of robustness in industrial

production, preventing disruption and ensuring that it can provide and support critical infrastructure in times of crisis.

To conclude, geopolitical changes and natural crises, together with the COVID-19 pandemic, have highlighted the fragility of the current approach to globalized production, which should instead be balanced by developing sufficiently resilient strategic value chains, adaptable production capacities and flexible business processes, especially where value chains meet basic human needs, such as health care or security.

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