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Utopian Environment of Sustainable Manufacturing in Industry 5.0: A review

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Abstract

A key sustainability concept is becoming more challenging than ever, with the increasing population rate, energy poverty, global warming, and surging demand for products and services. Sustainable manufacturing technologies research is growing to support our journey towards sustainable development. This systematic review intends to identify how sustainable manufacturing research is contributing to the development of the Industry 5.0 agenda and for a broader understanding of the links between Industry 5.0 and Sustainable Manufacturing by mapping and summarizing existing research efforts, identifying research agendas, as well as gaps and opportunities for research development. A conceptual framework formed by the principles and technological pillars of Industry 5.0, sustainable manufacturing scope, opportunities previously identified, and sustainability dimensions. Results point to that the current research is aligned with the goals defined by different national industrial programs. There are, however, research gaps and opportunities for field development, becoming more mature and having a significant contribution to fully developing the agenda of Industry 5.0.

1 Introduction

The manufacturing industry is currently in the fourth revolution after the period when artisans migrated from everyday craft to factories. The first revolution was manifested in product and process automation with the help of steam power and subsequently was accompanied by the widespread adoption of electricity. This was exacerbated by the computerization of manufacturing organizations' processes, and today we are experiencing the effects of Cyber-physical systems and advanced analytics also referred to as Industry 4.0. Several sustainable manufacturing frameworks have been identified as important to the growth of Industry 4.0 drives. These are Eco-efficiency and Industrial Symbiosis (Ferrera et al., 2017), Cleaner Production (Zhang et al., 2017; Sarkar et al., 2024, 2018, 2017), Sustainable Logistics Strandhagen et al. (2017), and Life Cycle Management (Cerri and Terzi, 2016). This new industrial paradigm is characterized by the link between high-tech with creativity and effective problem-solving for improving manufacturing with sustainability and inclusiveness. Contrary to previous industries, Industry 5.0 raises the issues of cooperation between man and a robot, especially using the service, collaborative robots – cobots. These cobots directly interact with human operators by performing monotonous and high-stress tasks which in turn frees up people to perform higher levels of activities within the manufacturing process. Besides increasing efficiency, this cooperation guarantees that people will not be replaced by robots but will receive additional help. Industry 5.0 attempts to shift the focus of the companies from

the ways of manufacturing or organizing the processes from human needs instead. Besides enhancing the workers' satisfaction and retention, this approach also allows them to be prepared to meet new challenges in the modern setting of manufacturing industries. Industry 5.0 has been supported by the European Commission and other related government departments. Manufacturing companies need to offer a higher return on investment and at the same time, environmental impacts should be reduced. It is also necessary for them to constitute an attractive workplace for people focusing on collaboration, learning, and the development of competencies. The 4th Industrial Revolution is an enabler of sustainable development, but the convergence of digital transformation and sustainability remains underdeveloped (Beier et al., 2018). Recently, some studies have identified several interlinks between Industry 5.0 technologies and sustainable operations. For instance, De Man and Strandhagen (2017) discuss the influence of Industry 5.0 on sustainable business models. Kamble et al. (2020) focus on the effects of Industry 5.0 technologies on Lean Manufacturing Practices for sustainable organizations. Ghobakhloo (2020) presents the dependence power of the determinants for Industry 4.0 implementation in the sustainability context. Blümel (2013) examines the possibilities of using virtual and augmented reality to develop human entities interfacing and learning.

However, this paper expands on the concept of how various technologies have been utilised in executing sustainable operations together with connecting these to numerous governmental-led best practices for Industry 5.0 implementation. In this case, we outline the research agenda that will help to meet these goals and identify new research directions in this area.

2 Background

The matters of Industry 5.0 can be described as a modern perspective that defines a clear and constructive vision of the industrial environment that is friendly to the environment and society. Unlike the third iteration, Industry 4.0, mainly because it relies on the fourth performance formula that emphasizes the use of technologies to enhance the productivity of an industry. In its original context, zero (0) aims at managing the general socio-environmental problems that have been occasioned by today's industrial processes. Industry 4.0 has led to outstanding developments in automation and connectivity enabled with the help of cyber-physical systems, the Internet of Things (IoT) included, as well as with the use of analytics. Nevertheless, there has been a noticeable preoccupation with technology and efficiency and as such, questions like the digital divide, pollution or socio-economic injustice have not received a lot of attention.

The opponents believe that Industry 4.0 is too close to neoliberal capitalism that focuses on receivables and shareholders' profits, without regarding social and environmental impacts. While Industry 4. Overall, while zero (0) has somehow led to some positive changes in the aspects of sustainable micro-environmental performance indicators like production yield and emission factors, they pale in comparison to the overall monetarization of business logic which zero (0) promotes. This has been followed by a call for a new paradigm that relies on technological motives while putting more consideration on human beings and the earth. Industry 5.0 signifies this new model. It is to combine the next-generation technologies including the CAI, trans-formational energy systems, and smart materials with human ingenuity and innovative skills. This has a positive impact towards human-automation cooperation whereby work performance is increased while working conditions and satisfaction are issued a top hat. Thus, by making individuals the core of the Industrial Revolution, Industry 5. Thus, zero (0) focuses on the up and re-skilling of workers to be in a position to produce outcomes to the demands of the new manufacturing world.

Industry 5.0 abroad has been very much supported by one of the key bodies that exists in the European region, which is the European Commission. The Commission's perception underlines that Industry 5.0 would be characterized by humanists who demonstrate an understanding of the rational agent. As of 2021, the European Commission published its Industry 5.0 which states nine promises for the development of a strong, ecological, and people-oriented European industry (Breque et al., 2021). By early 2022, the Commission claimed that Industry 4.0 was insufficient in dealing with the current climate change issues and social unrest, it placed Industry 5.0 as a new vision for the industry that reconfigures or reframes the contribution and purpose of value operations chains, business forms, models, the digital revolution, and other aspects in an increasingly interconnected business context. In essence, Industry

5.0. Hence, zero is a new paradigm for industrial practices, as it pursues the optimization of many-sided technology, human well-being, and environmental protection. It is trying to revamp the idea of value chains and business models in the context of digital enhancement of all aspects of life, to achieve a better future for the industry.

The Industry 5.0 concept has recently grown as an ideal future industry with consideration for the environment and people's interests. Critics of Industry 4.0 demonstrate how it contributes to practices of neoliberal capitalist models based on profit and shareholders' interests worsening problems such as regional disparities or environmental stressors. Industry 5.0 aims to address these shortcomings through the effective combination of human and robot cooperation to implement the concept of a smart business environment for optimizing the utilization of resources and recognition of economic principles. Sindhwani et al. (2022) identified that the scale of Industry 5. 0 is not limited to production industries; it covers other industry types including the agricultural and health industries. Özdemir and Hekim (2018) explain Industry 5.0, being a more advanced yet gradual development of Industry 4.0, toward achieving its goal of obviating the shortcomings of the practice through the application of symmetrical innovation. On the other hand, Kumar et al. (2021) have had negative perceptions towards this by arguing that Industry 4.0 or that it is at the Industrial 5 stage.

3 Basic Concept of Sustainable Manufacturing

Sustainable Manufacturing can be defined as the integration of processes and systems capable of producing high-quality products and services using less and more sustainable resources (energy and materials), being safer for employees, customers and communities surrounding, and being able to mitigate environmental and social impacts throughout its whole life cycle. Benefits of sustainable manufacturing include cost reduction through resource efficiency and regulatory compliance improvement, better brand reputation, new market access, less labor turnover by creating attractive workplaces, and a long-term business approach by creating opportunities to access financing and capital. The sustainable manufacturing scope in four areas with its respective objects and applied disciplines, which were used to classify the papers in the sample:

(i) Manufacturing technologies (how things are manufactured) with a focus on process and equipment (machine-tool, facility); linked disciplines are production engineering, factory planning, and operations management

(ii) Product lifecycles (what is to be produced) with a focus on product and services design; linked discipline is engineering design

(iii) Value creation networks (organizational context) with a focus on organizations of companies and manufacturing networks; linked disciplines are business economics and knowledge management

(iv) Global manufacturing impacts (transition mechanisms towards sustainable manufacturing) with a focus on studies about manufacturing impacts on the world, including society, environment, and economy.

(v) Different aspects can contribute to a positive sustainable manufacturing strategy implementation, among others, the development of sustainability indicators, policies and procedures, companies' cultures and internal conditions for sustainability, sustainable design strategies, and stakeholders' engagement for sustainability and technologies.

4 Industry 5.0

Industry 5.0 concepts are associated with the technical perspective of a Cyber-Physical-System (CPS) integrated into manufacturing operations and with Internet of Things (IoT) technologies into the industrial processes, which can be represented by smart factories, smart products, and extended value

networks – vertical, horizontal and end-to-end integration (Bogle, 2017; Waibel et al., 2017). People, machines, and resources are vertically linked, while companies are linked horizontally across the value chain as in a social network created by CPS. Terms including Industrial Internet, Integrated Industry, Factory of the Future, Smart Industry and Smart Manufacturing are also used to address similar requirements and are subsumed by the concept of 'Industry 5.0'. It is however perceived that they converge about the desirable features relating to being flexible and reconfigurable, low cost, adaptive or transformable, agile and lean. In the Industry 5.0 manufacturing system, simulation and modeling are critical to sustaining energy improvement, value addition in the supply chain, and to verify new tools and smart systems employed in the manufacturing process (Ferrera et al., 2017; Müller et al., 2018; Lee et al., 2014). This new industrial system is run by advanced manufacturing technologies. The set of 'pillars of technological advancement' are to be considered for this research:

(i) Autonomous Robots – the use of robots in production is evolving in their utility, increasing autonomy, flexibility, and interaction with humans and other robots.

(ii) Simulation – besides the use for simulating products, materials and production processes, simulation models can be used to improve plant operations creating a virtual model of the factory including all elements (machines, products and humans), also called digital twins.

(iii) Horizontal and Vertical systems integration – IT systems integration in the entire supply chain creating data-integration networks and internal cross-functions integration as well.

(iv) Industrial IoT – devices with embedded computing communicating and interacting in real time.

(v) Cyber security – integrated networks demanding protection for critical industrial systems, and manufacturing lines, and also to secure reliable communication and information flows.

(vi) Cloud – data-driven services and data sharing across different sites will be deployed in the cloud.

(vii) Additive Manufacturing (AM) – AM will enable small batch production of customized and lighter products, also reducing logistics costs and stocks.

(viii) Big data and analytics – It is the collection and analysis of large data sets from different sources supporting real-time decisions.

5 Relation between Industry 5.0 and sustainable manufacturing

Digitalization and sustainability are transversal themes crossing all parts of the production chain. Both approaches present practices' convergence, such as design for disassembly, remanufacturing, and recycling applied in the life cycle management; reverse logistics for the circular economy, 'lean and green management' for resource efficiency; sustainable design reducing safety risks for workers' and consumers' eliminating the use of toxic parts in the product and production processes. In general, sustainability benefits of Industry 5.0 are expected to improve productivity, flexibility, and resource efficiency (e.g. big data for predictive maintenance and fast production systems reconfiguration); reduce waste, energy consumption, and overproduction (e.g. renewable energy surplus shared with other plants); service and stakeholders' engagement/collaboration (e.g. closed-loop production systems connecting machines, information systems, products and people in a network); job opportunities related to IT competences; improvement of quality of working environment reducing routine jobs, e.g. creating employment opportunities for disabled and elderly employees. The Industry 5.0 can support value creation in all sustainability dimensions and, in this matter, they identify opportunities for industry development considering: (1) development of business models driven by smart data, offering new product-services; (2) closed-loop product life cycles and industry symbiosis creating value networks; (3) equipment using CPS for retrofitting SMEs (Small- and Medium-sized Enterprises) digitization; (4) training and

competence development supported by ICT technologies; (5) motivation and creativity fomented by programs supported by CPS (e.g. games and individual incentive systems for workers); (6) sustainable-oriented decentralized organization focused on resource efficiency; (7) sustainable process design using new technologies promoting closed-loop life cycles and cradle-to-cradle approaches. Each sustainability dimension represents a specific system evolving around a digital value-creation solution, so one adopted solution can create direct impacts on one dimension system but also have indirect effects on the other dimension systems of sustainability. The interactions between sustainability systems can occur in three different types: causal relations (effects between a solution and its direct and indirect impacts); magnitude and scale drivers; and latency and timely duration dependencies.

6 Sustainable opportunities

• *Business Model:* Integration of physical products and cyber-services during their whole lifecycle; new business model focused on meeting consumer needs – mass customization, exploiting new digital and other technologies enabling the transition to a fossil-free and circular economy. • *Production:* Reconfigurable, adaptive and evolving factories capable of small-scale production; high-performance production; zero-defect; near-to zero emissions; energy, water, land usage, heat management and resource efficiency; material kept in a 'productive loop'; low-carbon technology; cleaner factories; circular economy strategies; symbiotic manufacturing; sustainable, safe and attractive workplaces; highly vertical integrated; workers with the right knowledge and highly skilled. • *Supply Chain:* Supply chains with available capacity at all stages; energy and resource-efficient; higher level of collaboration and cooperation; highly integrated horizontally. • *Product:* New forms of value including sustainability; reused, remanufactured, recycled; shared ownership; reduced use of materials and energy; elimination of harmful substances; cradle-to-cradle approach. • *Policy Development:* Regulations and governance mechanisms incentivize/facilitate resource-efficient and environmentally friendly production; transparent, clear, and effective permit and supervisory processes.

7 Progression of Industry 5.0

The revolution of Industry 5.0 means that humans and machines are working together, improving the efficiency of industrial production. Human workers and universal robots are increasing the productivity of the manufacturing industry. Each of the executive teams of the manufacturing company is required to define the production line, and then follow the key performance indicators and ensure that the processes are working effortlessly. The future direction of Industry 5.0 is the manufacturing of robots and industrial robots. The advancement of artificial intelligence and cognitive computing technologies is taking the manufacturing world to a new level of speed and increasing business efficiency. In addition to the benefits in the manufacturing business, industry 5.0 also benefits sustainability as it aims to develop a sustainable system that runs on renewable energy.

8 Applications of Industry 5.0

8.1 Smart Hospital

The technology can provide remote monitoring systems within healthcare. It plays a key in making life better for the doctors. In the COVID-19 pandemic, doctors can use this smart healthcare technology to focus on infected patients and provide efficient data regarding better treatment. Even it also helps the students as well as medical students for needed medical training through the outbreak of COVID-19. Machine learning (ML) is applied to medical imaging, natural language processing, plus genetic data. It is focused on the diagnosis of the diseases, detection, plus prediction of the diseases. Medical professionals are moving towards artificial intelligence technology to measure various problems like glucose levels. It helps implement the technologies used in the revolution as it is helpful to perform the surgery in a

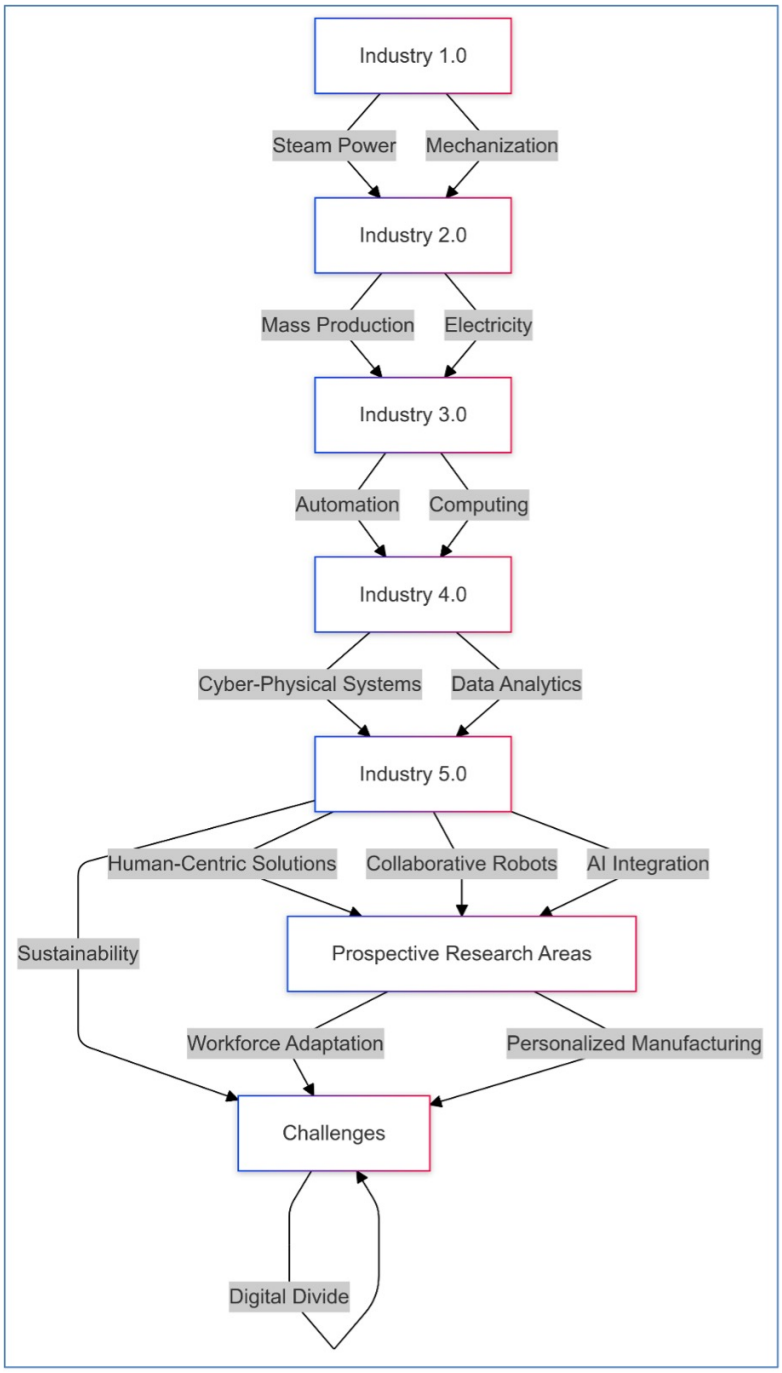

Figure 1: Industrial evolution (Industry 1.0 to 5.0).

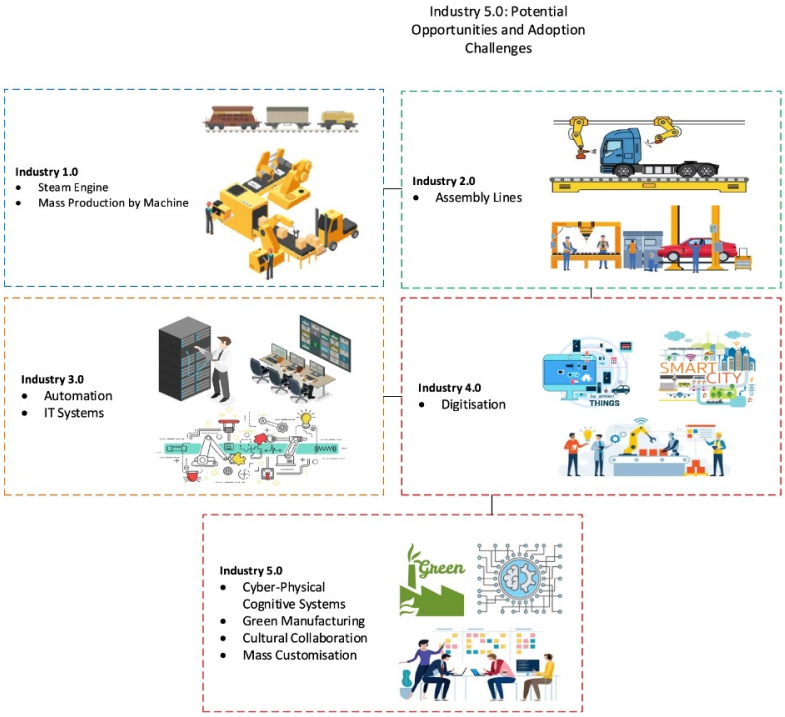

Figure 2: Industrial evolution (Source: Adel (2022)).

precise manner. It is helpful for medical students to provide better education, learning, and research and expansion procedures. In orthopaedics, industry 5.0 requires high-quality implants with an extended life that is personalized.

8.2 Manufacturing industry

Industry 5.0 is considered a new production model where it is focused on interaction among humans as well as machines. Industry 5.0 is involved in leveraging collaboration among increasing accurate machinery plus the innovative potential of human beings. To make manufacturing sustainable, it develops processes that repurpose and recycle the resources. There is also a need to reduce the environmental impacts in the manufacturing industry. Additive manufacturing is required to increase personalization to optimize resource efficiency and waste. Industry 5.0 is revolutionizing manufacturing systems across the globe by taking away repetitive tasks from human workers. Intelligent robots and systems are penetrating supply chains and manufacturing shop floors to an unparalleled stage. Smart manufacturing allows designers to protect design files of manufacturing items by storing them in the cloud with robust access control and usage of the manufacturing resources across various places. Fig. 3 pictorially illustrates several potential applications within Industry 5.0. The designers are permitted to place the manufacturing plants close to raw materials and areas with low manufacturing costs. Control of machines in the plant and operations of the manufacturing lifecycle are to be handled by cloud manufacturing. The service-oriented model helps manufacturing integrate production abilities with the services to provide the clients with proper solutions. Through business innovations, adding service factors to the production process aims to improve production efficiency, value-added, and market share for the manufacturing business. The cloud-based platform controls the manufacturing services, and it is used in a cost-optimized way. Cloud manufacturing is networked as well as a distributed system for the production resources.

8.3 Supply chain management

Supply chain 5.0 highlights the importance of collaboration between smarter machines like COBOTS and humans. Industry 5.0 is aimed to cater to the hyper-personalization moreover hyper-customization requirements of the customers, which require a combination of human originality plus the competence

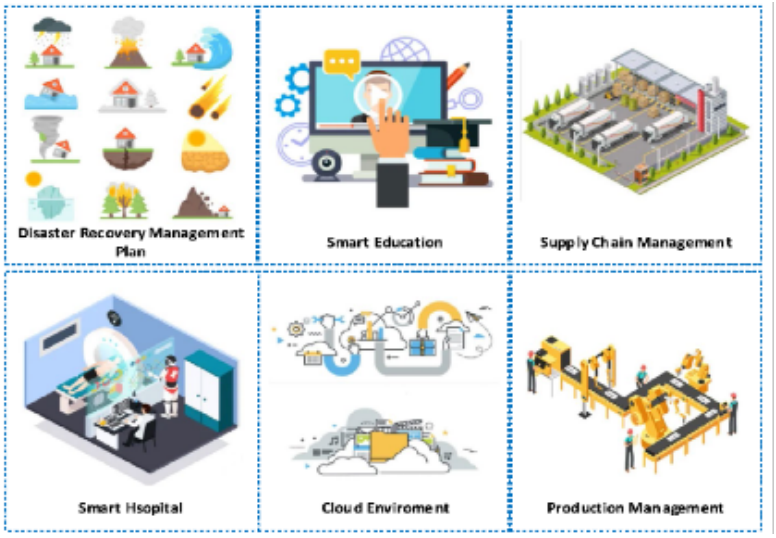

Figure 3: Applications of Industry 5.0 (Source: Adel (2022))

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of the machines. Robots are required for the supply chain management in standardized procedures in high production volumes, added this to each product, and it is a challenge where the robots are required proper guidance. The human touch is also not required to customize and personalized products. Still, it also ensures seamless end-to-end processes of the supply chain, such as selecting the raw materials to comprehend its personalization and customization needs for individual consumers. Industry 5.0 seeks to take automated and intelligent digital ecosystems and pair them with the human touch. There is leveraging of human elements in such a process that it helps customize the end-user experiences and optimized workflows. Human intelligence is worked in an empowered way with cognitive computing along with intelligent automation abilities to enable hyper-personalization. Technologies like machine learning, robotic automation, and others are helping employees increase business proficiency and deliver high value to customers faster. From delivering the raw materials, transactions, and transportation, the ERP system manages the supply chain for the business organization. The next generation of supply chain solutions is making and deploying the technology to empower the digital supply chain. It means bringing customization to the supply chain, improving the customer's satisfaction and the management of the business efficiency and market margins. There is a reduction of the risks related to supply chain and wastages based on the existing information of the business. The improvement of the supply chain integration for the strategic partnerships enabled the supply chains to spend time on experimentation plus less on the fighting forces on matters for the project executions.

9 Future scopes

In response to Industry 4.0, Industry 5.0 is defined as human-robot collaboration or the integration of skilled human work and advanced robotics systems. So, the dream of a sustainable manufacturing environment has been shaped and is being reshaped by the new trends and innovations that ensure the balance between man's imagination and emerging technologies. However, the essence of this change entails the symbiosis of human-oriented design together with intelligent solutions including artificial intelligence, the Internet of Things, and smart robotics. These technologies allow one to move away from completely automated processes to systems where man and machine complement each other. Smart factories are one important trend, it refers to the production manufacturing led by the real-time data of the production line of where to reduce waste or how to improve the energy consumption rate. Such an approach helps avoid negative influences on the environment while offering improved manufacturability and robustness of the systems involved. Thus, sustainable materials and circular economy practices are also focal to this 'post-technology' sociotechnical imaginary. Recycling technologies, remanufacturing

processes, and the usage of biodegradable materials also help in decreasing the carbon impression of production operations. Also, the advent of decentralized production systems due to the availability of 3D printing and other blockchain-enabled technologies support local industries hence cutting down on transportation-related CO_2 emissions and promoting local and community-based economies. In addition, the ethical component of such a shift in the Industrial Revolution or Industry 5.0 is becoming more widely known, where organizational policies promoting equality aim at skilled pay for everybody and diversity at workplaces. Sheltered working conditions embrace ergonomic designs, while the use of wearable technology comprises part of the strategies aimed at improving both the physical and mental health of the workers. Moving forward, the relations between the government and policymakers, companies, and academics will be essential regarding the implementation and development of those innovations together with corresponding regulations and educational programs. Concisely, it was found that the role of sustainable manufacturing in Industry 5.0 chronicles a harmonious integration of synthesis of technology and humanity to precipitate a revolution that not only fuels industrial increase but ensures compassionate sensitiveness to the environment and its people.

10 Conclusions

This paper contributes to advances in Industry 5.0 research identifying that the concepts of sustainable manufacturing and the use of new technologies can enable Industry 5.0 to have positive impacts on all the sustainability dimensions in an integrated way, and also supporting the implementation of the Industry 5.0 agenda in the following aspects: developing sustainable business models; sustainable and circular production systems; sustainable supply chains; sustainable product design; and policy development to ensure the achievement of the sustainable goals in the Industry 5.0 agenda. Results allow concluding that the field is legitimated but not consolidated; however, is evolving based on the development of new business models, and value-creation-chains integration. Results also allowed for designing a research agenda and scenario for further development of the field towards more normative studies focused on the processes of implementation of the Industry 5.0 agenda. This study is not meant to provide a more in-depth analysis of specific topics and limitations rely on the limited number of papers analyzed, the decision to not use statistical analysis and not considering cross-disciplinary topics that are being developed by other research fields. Future research can focus on the implementation of different advanced techniques, including computer vision (Pramanik et al., 2021), machine learning (Sarkar et al., 2019b, 2020, 2019a), and deep learning (Sarkar et al., 2022; Pramanik et al., 2022), enabling industries to achieve the full goals of Industry 5.0.

Conflict of Interest

The authors declare that there is no conflict of interest in this work.

Data availability

The authors do not have permission to share data.

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