Emerging Technologies in Industry 5.0: Sustainable Innovation for a Value-Driven Future

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Abstract. Industry 5.0 is an industrial model that evolves from the experience of Industry 4.0. However, this paradigm shift is aimed at establishing a hyper-connected industrial ecosystem driven by essential values that allow the achievement of the Sustainable Development Goals (SDGs). The present work examines the enabling technologies inherited from Industry 4.0 such as big data, augmented reality, or artificial intelligence, to determine to what extent they are beneficial for the worker in the new desired industrial context. Furthermore, the objective of this work is based on identifying and characterizing the new technologies that emerge from the core of Industry 5.0. This analysis establishes an essential foundation for the future development of innovative and competitive industrial systems that are also socially and environmentally responsible. Thus, this research contributes to the progress towards more ethical and sustainable industrial practices, aligned with the fundamental principles of Industry 5.0 and the global commitment to achieve sustainable development goals.

Keywords: Industry 5.0 · Enabling Technologies · Emerging Technologies · Industrial Sustainability · Sustainable Development Goals (SDGs)

1 Introduction

In a global context where social responsibility and sustainability are imperative, Industry 5.0 emerges as an industrial model that has evolved from the experience of Industry 4.0. This new paradigm represents not only a continuation of the technological revolution but also a fundamental shift towards a more ethical approach [1]. Industry 5.0 is defined as a hyper-connected industrial ecosystem guided by essential values. These values, understood as a guide in any process under the new industrial paradigm, enable the achievement of the proposed social, economic, and environmental sustainability objectives [2]. The aim is to achieve production environments that can adapt to market demands, with environmentally friendly policies, and where decisions are made considering social aspects such as equity, transparency, and respect for human rights [3] (see Fig. 1).

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The different industrial revolutions have occurred over time, taking decades to unfold. However, Industry 5.0 is emerging while many companies have yet to reach Industry 4.0 [4]. Leading researchers stand before two distinct perspectives that may explain this occurrence. The first perspective suggests that the development of disruptive technologies such as 6G, Artificial Intelligence, and Cognitive Computing is revolutionizing the future of the workplace, and this necessitates a new industrial paradigm to support it [5]. The second perspective holds a holistic technocultural view of the drivers of Industry 5.0 and posits that this phenomenon directly addresses two significant shortcomings of Industry 4.0: technology and human centrality [6]. Consequently, this study aims to analyze how enabling technologies are impacting humans and to identify the new technologies that are emerging within the realm of Industry 5.0.

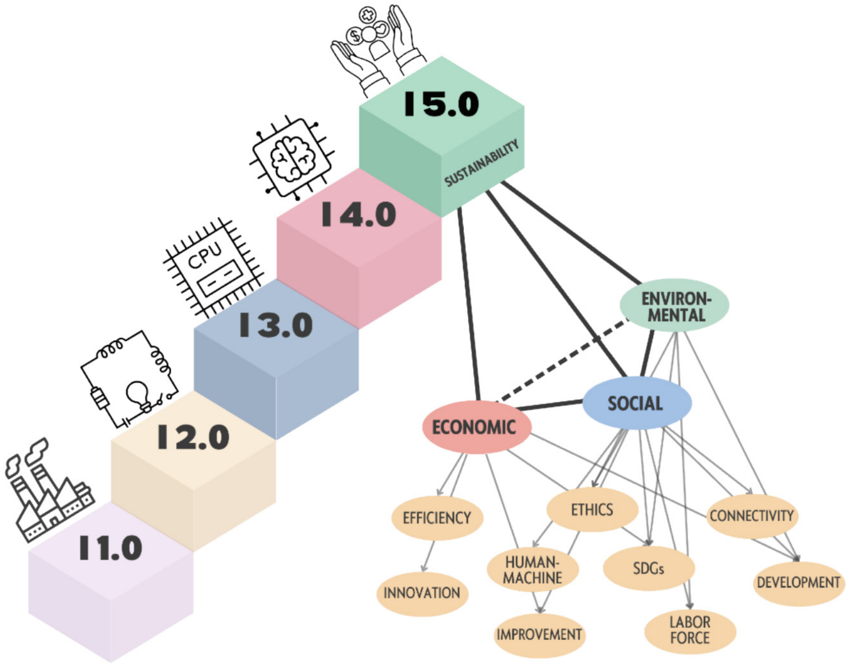

Fig. 1. Deployment of the Industry 5.0 objectives.

The Sustainable Development Goals (SDGs) were born at the United Nations Conference on Sustainable Development in 2012 [7]. These are a collection of 17 interconnected goals designed to achieve a sustainable future for everyone (see Fig. 2). These goals range from the elimination of hunger and poverty to combating climate change and promoting education and gender equality. They were established to continue the work of the Millennium Development Goals (MDGs) [8], but with a broader vision and a stronger commitment to inclusivity and environmental sustainability. The goals of Industry 5.0 align with the principles of sustainability and human well-being that underpin the SDGs. In this context, enabling technologies are used as key tools to effectively address the challenges posed by the SDGs. For example, resource optimization through artificial intelligence can make a significant contribution to SDG 12, which promotes responsible production and consumption. Similarly, additive manufacturing and collaborative robotics can revolutionize production chains, reducing waste and improving working conditions, positively impacting SDGs 8 and 9, which seek to promote decent work and industrial innovation. Moreover, the digitalization enabled by Industry 5.0 can improve product traceability and strengthen local economies, supporting SDG 11 on sustainable cities and communities.

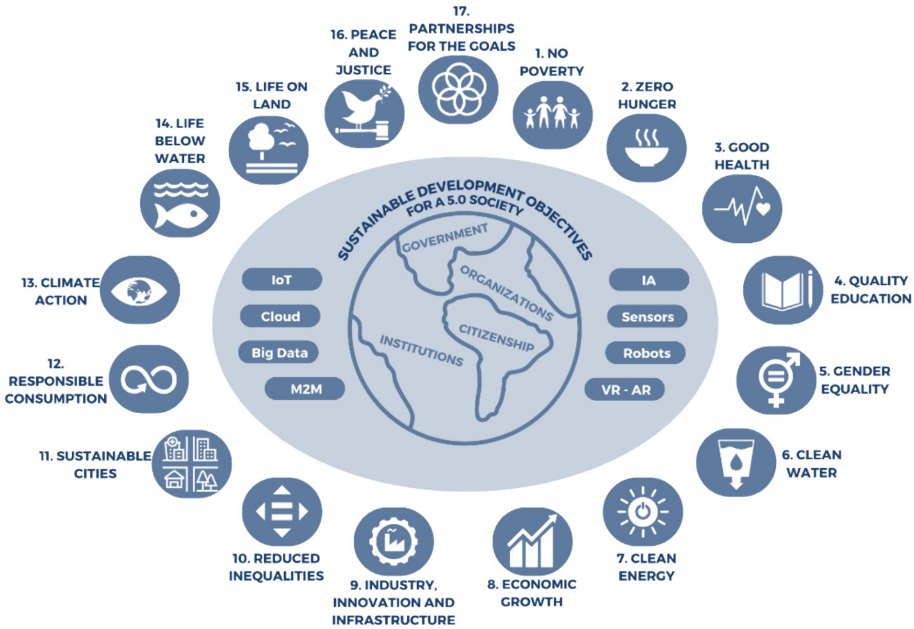

Fig. 2. Sustainable Development Goals (SDGs).

2 Literature Review

Enabling technologies of Industry 4.0 represent the set of technological innovations that emerged at the beginning of the 21st century. These marked the beginning of the fourth industrial revolution [9]. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), and robotics have transformed the manufacturing industry by offering greater efficiency, cost reduction, and production customization [10]. However, their implementation has not been without controversy regarding social and sustainable principles. Industry 4.0 technologies have created safer work environments and have contributed to a more robust economy and a lower environmental impact by optimizing resource use [11]. However, they have raised concerns related to job loss due to automation, the increasing skills gap, and potential ethical issues associated with AI [12, 13]. Table 1 classifies the main benefits and challenges that characterize each of the main enabling technologies.

Table 1. Enabling Technologies of Industry 5.0: Benefits and Challenges.

Technology	Benefit	Challenge
Augmented Reality	Enhanced training opportunities, agile task supervision, minimizes errors, support in decision-making processes, and better communication through efficient information exchange	Eye strain, user distraction, physical discomfort due to the weight of devices, a decrease in job satisfaction, and heightened stress levels
Virtual Reality	Facilitates operational execution, enhances cognitive abilities, and reduces dependence on physical documentation	Damages the decision-making capacity of workers, compatibility issues with safety equipment, reduces visual clarity, and limits field of vision of users
Autonomous Robots	Alleviates mental and physical stress, reduces risks associated with health in the workplace, improves the monitoring of production processes, and makes jobs more attractive	Leads to the reduction of human job positions, adds complexity to tasks, and faces challenges with worker acceptance
Collaborative robots	Streamlines complex tasks, enhances operational safety, reduces the margin of error, lessens the need for manual labor, and helps workers with physical challenges	Poses safety and ergonomic challenges, can increase anxiety among workers
Wearable Devices	Provides real-time monitoring of employee locations, enhances workplace safety, improves working conditions, assists in the precise measurement of time and quality metrics, and increases ergonomic awareness	Concerns about the privacy of collected data, difficulty adapting to different body types, and the psychophysical measurements they perform may be perceived as invasive
Artificial Intelligence	Reduces worker downtime, assists the worker in decision-making, and provides direct assistance in unfamiliar situations for the worker	Creates skepticism among workers and ethical concerns
Big Data	Personalization of services and products according to individual consumer preferences and advances in worker safety and health through the collection of a large amount of data	Privacy infringements for individuals and energy consumption for storing and processing large datasets

(*continued*)

Table 1. (*continued*)

Technology	Benefit	Challenge
Digital Twin	Decreases the effects of operational disruptions, increases the efficiency of daily tasks, reduces maintenance expenses, and leads to optimal resource utilization	Complexity in managing and analyzing large amounts of data and vulnerabilities to cyberattacks that could lead to the theft of sensitive information
Cloud Computing	Decreases the frequency of persistent problems and propels the process of continuous improvement in various operations	Concerns about the protection of sensitive corporate intelligence against breaches and unauthorized access
Internet of Things (IoT)	Efficiency in production, reduces waste, real-time data collection and examination, and fosters ideas that aid the worker	Worker resistance to technological change, complexities in integration, usability and acceptance difficulties, and concerns about system security

The duality of technologies reflects the challenge of balancing technological innovation with its social, economic, and environmental repercussions. This is a central theme that Industry 5.0 seeks to address.

3 Results and Discussion

The technologies of Industry 4.0 offer benefits in the industrial environment primarily related to efficiency, cost reduction, and improved production quality. However, these benefits do not always translate into greater well-being for workers and the environment [12]. Ethical and environmental challenges, such as data privacy, cybersecurity, and waste management, are critical issues that need to be addressed in the new industrial paradigm. For this, this context establishes guiding values to be respected throughout all design processes. Adapting existing technologies and developing new solutions under this premise is essential to bridge the gap between economic benefits and social and environmental responsibility in the industrial environment [14].

The *enabling technologies* of Industry 5.0 consist of digital technological developments integrated with cognitive abilities and innovation. These enabling technologies can be further categorized into *facilitating technologies* and *emerging technologies*. Facilitating technologies refer to those developed under the paradigm of Industry 4.0, which provide various benefits that align with the goals of Industry 5.0. However, with the development of the new industrial paradigm, a set of emerging technologies has emerged. These emerging technologies are presented as disruptive innovations based on facilitating technologies to drive more efficient methods of value creation. Table 2 lists the 9 identified emerging technologies.

Table 2. Emerging Technologies of Industry 5.0.

Technology	Description
Cognitive Artificial Intelligence (CAI)	Cognitive Artificial Intelligence is the product of integrating Artificial Intelligence (AI) and Artificial Consciousness [16]. Existing AI systems face reliability issues in their implementation in cyber-physical systems (CPS). Experts believe that CAI will enable a better understanding of the external world to learn and act like a human being. CAI aims to assist stakeholders in making better decisions, reducing information overload, decreasing errors, improving health and safety, and generating more sustainable products and services [17]
Extended Reality (XR)	Extended Reality is a term used to encompass various immersive technologies. XR technologies offer numerous benefits to stakeholders in Industry 5.0. Improved customer experience, industrial training, and enhanced safety and efficiency in industrial processes are some examples [18]
Human Interaction and Recognition Technologies (HIRT)	Human Recognition and Interaction Technologies play a significant role in the human-centered goal of Industry 5.0. Currently, no detection and cognition technology has the emotional intelligence needed to seamlessly assess constantly changing working conditions and arrive at the best replica of what humans would do in a given situation [19]. HIRT aims to interconnect and integrate humans with machines optimally so that the resulting human-machine interaction offers safer and optimized physical and cognitive tasks [20]
Cognitive Cyber-Physical Systems (C-CCP)	Cognitive Cyber-Physical Systems are an upgrade from Cyber-Physical Systems, focusing on the role of human cognition in CPS, offering a smoother and safer human-machine interaction in all operations. C-CCPs are expected to be effective in fault detection and correction as well as informed decision-making [21]

(*continued*)

Table 2. (*continued*)

Technology	Description
Industrial Smart Wearable (ISW)	Industrial Smart Wearables would allow workers to perform their tasks more safely, quickly, and productively. There is already a diverse and growing range of emerging ISWs that offer various functionalities in line with the goals of Industry 5.0. However, within this context, advances are expected to continue addressing the capabilities and physiological needs of workers [22]
Intelligent Energy Management System (IEMS)	The Intelligent Energy Management System promotes energy efficiency through real-time monitoring and control of energy systems, improving their reliability. This technology helps bridge the gap in the development of renewable energy resources and their integration into industrial and commercial operations [23]
Intelligent or Adaptive Robots	Intelligent or adaptive robots define the next generation of industrial robotics with a higher level of human-centered automation. Traditional robots are fast and productive but need to be isolated by physical barriers for safety reasons. Collaborative robots, on the other hand, collaborate safely but at a slower speed. Intelligent robots are capable of adapting to complex environments and novel situations while performing a broader set of complex tasks [24]
Dynamic Simulation and Digital Twin (DSDT)	Dynamic Simulation and Digital Twin Technologies recreate digital representations of existing physical systems to proactively and cost-effectively address design inefficiencies and performance concerns. DSDT is essential for the sustainability goals of Industry 5.0 as it allows simulating and predicting the digital socio-environmental footprint of a products in a company [25]
Smart Product Lifecycle Management (SPLM)	Product Lifecycle Management systems enable a more robust integration of processes across the value network [26]. SPLM aims to provide authorized control over product and process data and improve manufacturing productivity, operational agility, environmental compliance, product quality, and end-of-life management [27]

4 Conclusions

In the context of the new industrial paradigm, enabling and emerging technologies are the essence of a digital symbiosis that reconfigures the relationship between industry and its environment. The confluence of Cognitive Artificial Intelligence and Cognitive Cyber-Physical Systems, with their learning and adaptation capabilities, offers a unique opportunity to address emerging social challenges, while enabling a closer and safer collaboration between humans and machines, and promoting decision-making based on deep data and predictive analysis.

Sustainability is more than a goal in Industry 5.0: it is the principle that governs all operations and decisions. The implementation of technologies such as Intelligent Energy Management Systems not only maximizes energy efficiency but also reflects a paradigm shift towards production that is conscious of environmental impact. This ecological awareness extends beyond business strategy; it is a testament to corporate social responsibility and a firm commitment to environmental preservation and social equity.

The challenges that arise from Industry 5.0 are complex. Among these, cybersecurity issues that can compromise workers, or the ethics in the use of artificial intelligence, stand out. Overcoming these challenges becomes a driver of innovation and technological development, which in turn strengthens infrastructures and increases trust and security in the industrial ecosystem. Addressing these challenges not only improves the resilience and adaptability of industries to disturbances but also promotes an environment of open and collaborative innovation, essential for long-term sustainability.

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