The Industry of the Future: From Industry 4.0 to Industry 5.0 – Integration of Humans and Technology: New Technologies

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Industry 4.0 vs. Industry 5.0: Evolution of System Structures from Digitalization and Cybernation to Cognitization

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Abstract: *The Fourth Industrial Revolution (Industry 4.0) has transformed manufacturing by introducing the concept of Smart Manufacturing Systems (SMS), enabling digitalization and automation of processes. This transition has led to a significant reduction in human intervention and an overall increase in production efficiency. Cyber-Physical Production Systems (CPPS) have played a crucial role in enhancing connectivity, adaptability, and intelligent management of manufacturing processes.*

Industry 5.0 introduces a new paradigm that goes beyond mere automation and digitalization—it integrates human-machine collaboration, cognitive technologies, and artificial intelligence (AI) to create adaptive, sustainable, and intelligent manufacturing systems. A key enabler of this new generation of production systems is the Cognitive Cyber-Physical Production System (C-CPPS), which facilitates autonomous decision-making, enhanced flexibility, and deeper integration between humans and machines.

This paper analyzes the fundamental differences between Industry 4.0 and Industry 5.0, focusing on the impact of digitalization, cybernation, and cognitization on the evolution of manufacturing systems. It further examines the technological challenges and opportunities associated with implementing AI and cognitive systems in production processes, with an emphasis on improving human-machine interaction and advancing sustainable industrial development.

Keywords: *Industry 4.0, Industry 5.0, digitalization, cybernation, cognitization, smart manufacturing systems, cyber-physical production systems, artificial intelligence, human-machine interaction.*

1. Introduction

The evolution of industrial revolutions has been a critical driver of technological and economic progress, facilitating breakthroughs in production efficiency and capacity across distinct historical periods. The origins trace back to the First Industrial Revolution (Industry 1.0), marked by the introduction of the steam engine, which catalyzed the mechanization of manufacturing processes. The Second Industrial Revolution (Industry 2.0), driven by the widespread adoption of electrification, enabled large-scale mass production and significantly

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enhanced productivity. The Third Industrial Revolution (Industry 3.0) introduced automation, which brought about substantial improvements in process control, operational flexibility, and integration of electronic systems within manufacturing [1], [2], see Fig. 1.

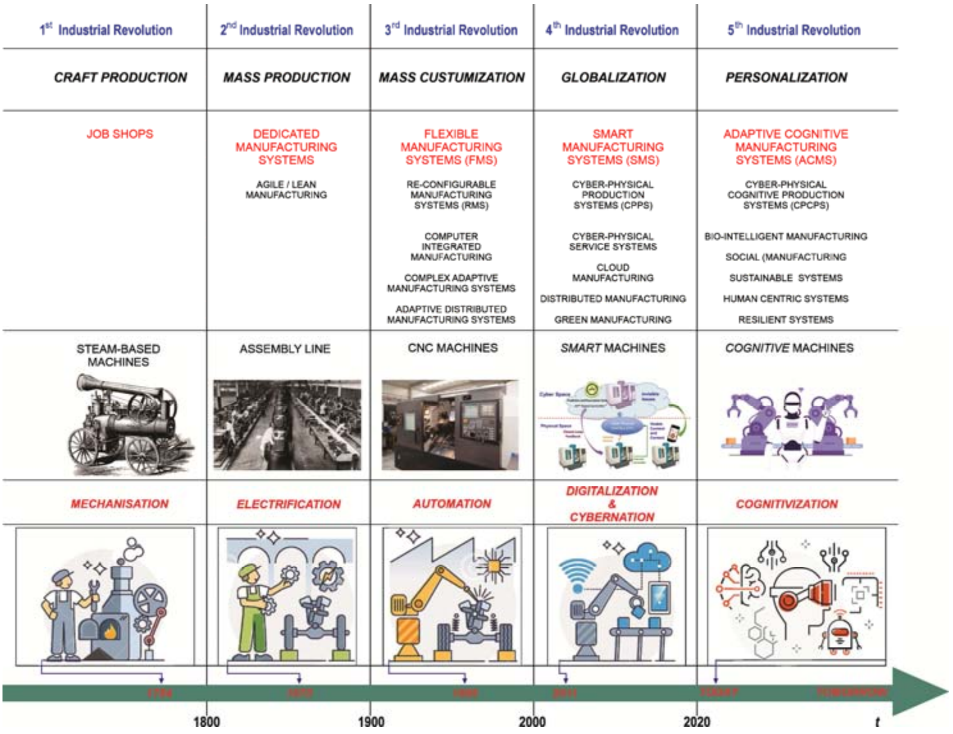

Figure 1. Timeline of Industrial Revolutions[2], [3]

Building upon these foundations, Industry 4.0 represents a transformative leap, characterized by the integration of *Smart Manufacturing Systems* (SMS) empowered by advanced digital technologies. Central to this paradigm are Artificial Intelligence (AI) [4], the Internet of Things (IoT) [5], and Cyber-Physical Production Systems (CPPS) [6], [7], which collectively enable autonomous decision-making, real-time process monitoring, and dynamic system optimization within the manufacturing environment. These developments have laid the groundwork for a new era of intelligent, interconnected, and adaptive industrial ecosystems [8], [9], [10], [11].

Industry 4.0 [8], [12], [10], [13]has introduced full automation, digitalization, and cyber-physical integration into the industrial ecosystem, resulting in enhanced productivity, increased operational efficiency, and significant reductions in manufacturing errors. However, the pursuit of complete automation also raises critical questions regarding the role of humans within the production process. The potential marginalization of human creativity, intuition, and adaptability presents a growing concern in highly automated environments.

In response to these challenges, the emerging paradigm of Industry 5.0 [14], [11]is gaining traction. Unlike its predecessor, Industry 5.0 emphasizes not only technological sophistication but also the human-centric integration of advanced systems[15], [16]. It promotes close collaboration between humans and intelligent machines, leveraging the strengths of both to foster resilient, adaptive, and sustainable manufacturing ecosystems[17], [3]. This paradigm shift marks a transition from purely efficiency-driven automation toward value-driven production that balances technological innovation with social and environmental responsibility[1]. Industry 5.0 builds upon the foundations of Industry 4.0 by advancing the integration of cognitive systems and fostering synergistic collaboration between humans and technology. At the core of this emerging paradigm is the implementation of Cognitive Cyber-Physical Production Systems (C-CPPS)[2], [3], which facilitate adaptive, context-aware, and intelligent manufacturing processes. These systems are characterized by their ability to perceive, learn, and make autonomous decisions in real time, enabling unprecedented levels of flexibility and responsiveness in production.

The transition toward Industry 5.0[9] is underpinned by key enablers such as advanced Artificial Intelligence (AI), Machine Learning (ML), and embedded decision-making architectures, which collectively support the development of smart, self-optimizing systems. The overarching objective of Industry 5.0 is to establish sustainable and innovation-driven production environments that enhance workplace quality, increase operational efficiency, and strengthen the human-machine interface. This paradigm envisions a future in which technological advancement is harmonized with human-centric values and ecological responsibility.

The evolution of industrial systems—from mechanization, electrification, and automation to digitalization, cyber-physical integration, and now cognitization—marks a significant milestone in the advancement of manufacturing (Fig. 1)[3]. While Industry 4.0 has enabled production optimization through autonomous processes and intelligent systems, Industry 5.0 places renewed emphasis on the human factor and its synergistic interaction with emerging technologies.

In this new paradigm, the development of cognitive systems plays a central role. These systems support advanced decision-making, context-aware adaptability, and real-time responsiveness, all while aligning technological advancement with the goals of sustainable industrial growth. The transition toward a human-centric, intelligent manufacturing ecosystem thus not only enhances productivity and resilience but also redefines the future of work within the industrial domain.

This contribution offers an in-depth examination of the distinctions between Industry 4.0 and Industry 5.0, with a particular focus on the transformative impact of digitalization, cyber-physical integration, and cognitization on modern manufacturing processes. The analysis explores both the technological challenges and the practical opportunities associated with the implementation of artificial intelligence and cognitive systems, which enhance human-machine interaction and enable intelligent decision-making.

Moreover, the study highlights the importance of sustainable development, alongside the ethical and security implications of integrating emerging technologies into industrial environments. By addressing these critical dimensions, the article contributes to a more comprehensive understanding of the future trajectory of industrial production and the evolving role of humans within next-generation intelligent manufacturing systems.

2. Methodological Framework

To achieve the research objectives, a multi-stage methodological approach was employed. In the initial phase, a systematic review of scientific literature pertaining to Industry 4.0 and Industry 5.0 was conducted. The review focused primarily on core concepts such as digitalization, cyber-physical integration, and cognitive technologies. To ensure comprehensive coverage and academic rigor, relevant literature was sourced from reputable scientific databases, including Web of Science, Scopus, and Google Scholar.

Based on the insights obtained during the initial phase, a comparative analysis was conducted to examine the key characteristics of the Industry 4.0 and Industry 5.0 paradigms. Special attention was given to the differences and similarities in technological approaches, deployed system architectures, and their respective impacts on operational efficiency, sustainability, and the role of humans within production processes.

Furthermore, a qualitative assessment was conducted to evaluate the technological challenges and opportunities associated with the implementation of cognitive technologies in manufacturing systems. The study also explored in greater detail the potential barriers that companies encounter during the transition from Industry 4.0 to Industry 5.0, with an emphasis on organizational readiness, technological integration, and human-machine collaboration.

In the final stage of this research, the author presents a synthesis of the collected data and analyses, culminating in concrete recommendations for the effective implementation of Industry 5.0 concepts within manufacturing environments. Based on these findings, the study also identifies directions for future research, particularly in the development of intelligent manufacturing systems. This methodological framework provides a comprehensive overview of the examined concepts and ensures both the systematic structure and scientific validity of the study’s final conclusions.

2. Industry 4.0

2.1. Globalization

Globalization has played a pivotal role in shaping and accelerating the adoption of the Industry 4.0 paradigm. It has enabled manufacturing enterprises to operate within an international context, where they face not only local but also intensified global competition. This dynamic has necessitated the development and deployment of advanced technologies and processes that support a high degree of automation, digitalization, and the efficient management of globally distributed production networks. As a result, globalization has become a key driver in the transformation toward smart, interconnected, and responsive manufacturing systems[18], [3].

With the advancement of information and communication technologies (ICT), as well as the digitalization and cyber-physical integration of manufacturing processes, globalization has become a foundational element of Industry 4.0[19], [20], [21], [7]. It enables the seamless interconnection of production units across the globe into a unified, integrated system. This interconnectivity facilitates faster information exchange, reduced production costs, enhanced product quality, and greater flexibility in manufacturing systems. Companies that leverage Industry 4.0 technologies are able to manage their operations more efficiently and respond rapidly to market fluctuations and consumer demands at a global scale.

On the other hand, globalization also introduces significant challenges, including logistical complexity, heightened cybersecurity risks, and the critical need for technological standardization and interoperability at the international level. Consequently, the successful implementation of Industry 4.0 concepts requires continuous investment in technological innovation, ongoing workforce education and training, as well as the effective management and protection of information systems. These elements are essential to ensuring resilience, competitiveness, and secure operations in a globally connected industrial landscape.

The contribution of globalization to Industry 4.0 is most evident in the enhanced capabilities for networked collaboration among enterprises, the improvement of global competitiveness, and the increased adaptability of organizations to fluctuations in international markets. In this context, globalization can be regarded as one of the fundamental pillars and key enablers driving the development and widespread implementation of Industry 4.0.

2.2. Digitalization and Cybernation in Manufacturing

Digitalization and cybernation are fundamental components of Industry 4.0, significantly transforming traditional manufacturing processes[3]. Digitalization refers to the conversion of analog operations into digital formats and their execution through digital mechanisms, enabling the efficient collection, storage, and analysis of large volumes of data. This transformation serves as the basis for data-driven decision-making, process optimization, and the development of intelligent, interconnected production environments[7].

The operations carried out within digitalized processes are referred to as digitalized functions, as illustrated in Fig. 2a. These functions are executed in a fully automated manner. The corresponding digital mechanisms are embedded in software systems—either based on traditional algorithmic solutions or enhanced through artificial intelligence—which enable the execution of digitalized functions.

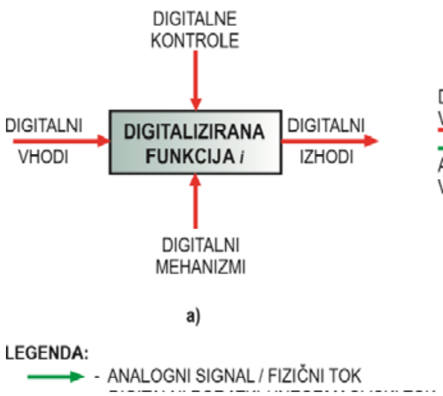

Figure 2. Digitalized and cybernated functions

Digital controls represent the digital embodiment of control mechanisms (e.g., constraints, rules, protocols), governing the execution of these functions. Examples of digitalization within the manufacturing domain include material ordering, production planning, procurement within supply chains, accounting, and financial transactions, all of which benefit from increased efficiency, traceability, and responsiveness enabled by digital transformation.

The application of digital technologies provides manufacturers with enhanced visibility and control over their operational processes. This enables real-time production monitoring, the execution of predictive analytics, and the ability to make faster and more informed decisions. As a result, such capabilities lead to a reduction in errors and production downtime, thereby contributing to higher product quality and improved efficiency across manufacturing lines.

Cybernation complements digitalization by introducing advanced automation and connectivity into manufacturing systems. It encompasses the intelligent, computer-based management, control, regulation, and supervision of physical elements within the production environment—including processes, machinery, equipment, and human operators—through the use of digital computing components such as programmable logic controllers (PLCs), digital processors, control software, and databases[7], [3].

The operations executed within cybernated processes are referred to as cybernated functions, as illustrated in Fig. 2b. These functions operate within a hybrid environment, bridging the analog and digital domains, where both inputs and outputs can be of analog or digital nature.

The execution of cybernated functions is enabled by a combination of digital mechanisms—such as algorithms, software agents, expert systems, genetic algorithms, and databases—and physical analog mechanisms, including process-executing devices, actuators, and sensors. Similar to digitalized functions, digital controls in this context serve as formalized rule sets or instructions that regulate the behavior and coordination of these hybrid systems[7], [3].

Cybernation enables seamless communication among various components of the manufacturing system—including machines, devices, and software platforms—facilitating automatic process control and adaptive responses to dynamic market conditions. This level of integration supports the creation of highly flexible manufacturing systems capable of rapid adaptation to changing demands and external disruptions.

Despite its numerous advantages, the implementation of digitalization and cybernation also presents significant challenges. These include the complexity of integration, high initial investment costs, the demand for new employee competencies, and security risks inherent to digital environments. Therefore, for companies to fully capitalize on the potential of Industry 4.0, it is essential to strategically invest in technological development, workforce training, and robust cybersecurity measures.

2.3. Enabling Technologies of Industry 4.0

Information and Communication Technology (ICT) serves as the cornerstone of the modern digital economy and has had a profound impact on the transformation of business processes within manufacturing enterprises.

Over the past three decades, the introduction of the ICT has driven one of the most significant transformations in the functioning of manufacturing systems. As noted by Weill and Broadbent [22], ICT encompasses all tools and equipment used to capture, process, analyze, and store data, with the objective of supporting and optimizing both business and production processes.

In the manufacturing domain, ICT is integrated into a variety of information systems, including Executive Support Systems (ESS), Management Information Systems (MIS), Decision Support Systems (DSS), Knowledge Management Systems (KMS), Transaction Processing Systems (TPS), Office Automation Systems (OAS), Expert Systems (EIS), and Workflow Support Systems (WSS). The functionality of these systems is not strictly delineated, but rather frequently overlaps in practice, enabling more comprehensive and dynamic support for production and managerial activities.

Advanced solutions such as Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), Customer Relationship Management (CRM), Manufacturing Execution Systems (MES), Supervisory Control and Data Acquisition (SCADA), and CAD/CAPP/CAM systems enable comprehensive digital management of manufacturing processes. However, their integration often encounters challenges due to a lack of standardization and interoperability, which remains one of the major obstacles in modern digital manufacturing environments.

Among the core functions of information systems are the acquisition, processing, organization, storage, and transmission of data. Reliable management of these processes enhances operational efficiency, reduces costs, improves understanding of customer needs, and shortens order fulfillment times.

In addition to the previously discussed information and communication technologies—such as ERP, MES, SCADA, IoT, IoS, cloud computing, and multi-agent systems—Fig. 3 highlights several other key enabling technologies, which are further elaborated in the following sections.

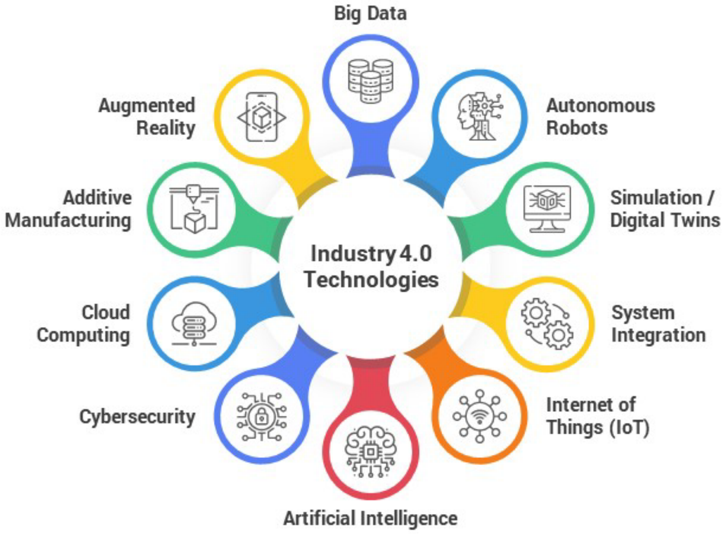

Figure 3. Enabling Technologies of Industry 4.0

With the increasing digitalization and interconnectivity of manufacturing systems, there is a growing need to protect information and production infrastructures from cyberattacks. Cybersecurity encompasses a set of policies, technologies, and processes aimed at safeguarding data, software, devices, and networks. Without a robust cybersecurity framework, the operation of a smart factory is exposed to significant risks, potentially compromising system integrity, reliability, and operational continuity.

Artificial Intelligence (AI) enables advanced data processing, decision-making, and experience-based learning. It is employed to optimize processes, predict maintenance needs, manage supply chains, and support mass customization in production. The integration of AI with the Internet of Things (IoT), Big Data, and digital twins facilitates the development of self-adaptive manufacturing systems capable of real-time responsiveness and optimization.

Digital twins are virtual representations of physical systems that enable continuous monitoring, simulation, and real-time optimization of industrial processes. Through simulation capabilities, companies can predict system behavior, test alternative scenarios, and fine-tune production parameters without physical interventions. Digital twins are essential for predictive maintenance and the implementation of changes with minimal disruption to operations.

The integration of diverse manufacturing and information systems—such as ERP, MES, SCADA, CRM, and others—enables seamless data flow, enhanced process transparency, and improved coordination across functional domains. A systematic linkage between the operational level and the strategic and informational environment ensures effective decision-making and coherent coordination throughout the entire organization.

Autonomous robots equipped with sensors, AI, and connectivity capabilities are capable of performing complex tasks without continuous human supervision. They are essential for operations that require high precision, speed, and adaptability. When integrated with AI, these robots can operate in heterogeneous work environments, dynamically adapting to changes in production conditions and collaborating with other systems and human operators in real time.

Big data generated by sensors, machines, and users necessitate the use of advanced analytical approaches. Big Data technologies enable the identification of patterns, production optimization, error reduction, and data-driven decision-making. Big Data serves as the foundation for predictive maintenance, market analysis, and real-time responsiveness to demand fluctuations, making it a critical enabler of intelligent and adaptive manufacturing environments.

Real-time optimization enables the immediate adjustment of production parameters in response to changing environmental and operational conditions. It is applied in control systems, logistics, task coordination, and energy efficiency management. The key value of this technology lies in its ability to minimize time losses and enhance the flexibility of manufacturing systems, thereby supporting responsiveness and resilience in dynamic production environments.

Cloud computing enables the storage, access, and analysis of data via the internet, offering a flexible and scalable infrastructure for modern manufacturing environments. Its key advantages include reduced infrastructure costs, scalability, and remote access to production data in real time. Cloud services support the implementation of Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) models, thereby facilitating the flexible execution and integration of various functions within manufacturing systems.

The internet forms the foundation of modern digital communication technologies and enables the creation of smart environments, such as the Internet of Things (IoT) and the Internet of Services (IoS). The IoT connects physical objects through sensor networks, wireless communication, and IP protocols, enabling the automatic detection, collection, and exchange of data across systems and devices. The IoS builds upon this concept by offering platforms and services based on SaaS, PaaS, and IaaS models, which support business operations through web-accessible applications and cloud-based infrastructure.

Social networks also play an important role in supporting manufacturing processes by enabling new forms of interaction within the production system from the perspective of organizational communication, collaboration, and responsiveness. These interactions involve not only human actors, but also machines and devices, fostering a more integrated and communicative manufacturing environment. The inclusion of smart devices within web-based social networks further expands the capabilities for monitoring, control, and coordination across various elements of the production ecosystem.

Communication technologies such as Modbus, ProfiBus, PROFINET, Ethernet/IP, and wireless networks (e.g., WiFi, ZigBee, Bluetooth) enable real-time information exchange between distributed units within the manufacturing system. These standards support reliable and high-speed communication, serving as a foundational element for effective automation and digital control in modern industrial environments.

Machine learning enables systems to automatically learn from data, identify patterns, and predict future events. It is widely applied in process optimization, predictive maintenance, and anomaly detection in product quality. In conjunction with Big Data, machine learning serves as a key enabler for the development of self-learning systems in modern manufacturing environments.

Augmented Reality (AR) bridges the physical and digital environments, enabling operators to access real-time visualizations of device information, work instructions, alerts, and diagnostics. AR is frequently applied in employee training and maintenance procedures, improving operational efficiency and safety.

Additive manufacturing (AM) facilitates the production of complex geometries directly from digital models without the need for conventional tooling. Key advantages include rapid prototyping, reduced material consumption, and the ability to personalize products. Within the Industry 4.0 framework, additive manufacturing represents a critical step toward decentralized and flexible production systems.

2.4.Cyber-Physical Production Systems

To understand the concept of Cyber-Physical Production Systems (CPPS), it is essential to first define the notion of cybernetics. The term originates from the Greek word *kubernēin*, meaning *to govern* or *to steer*. As a scientific discipline, cybernetics gained prominence through the work of Norbert Wiener, who in 1948 published the seminal book *Cybernetics: Or Control and Communication in the Animal and the Machine*. In this work, Wiener laid the foundation for understanding control and communication mechanisms in both biological and technical systems[23],.

The understanding of cyberspace expanded significantly during the 1980s, particularly through the work of William Gibson[24], who popularized the term in his literary writings. Subsequently, various authors—among them Michael Benedikt [25] and Michael Heim[26]—offered additional interpretations of the nature of this space, describing it as an artificial informational realm shaped by the interaction between data, technology, and humans. Within this environment, multiple actors—including machines, algorithms, and people—interact, exchange information, and make decisions, forming the basis of intelligent, distributed systems.

Building upon this foundation, Cyber-Physical Systems (CPS) [6]have emerged as a new generation of complex, integrated systems, where physical and digital components are tightly interconnected. According to definition [27], CPS combine computational and communication capabilities to monitor and control events occurring in the physical environment. These systems are composed of sensors, actuators, control units, and communication interfaces, operating as networked agents. This infrastructure enables the real-time collection and processing of data, allowing for rapid adaptation of system responses to dynamic conditions.

Cyber-Physical Production Systems (CPPS) represent the implementation of CPS within manufacturing environments. According to Monostori et al.[28], CPPS are defined as systems comprising autonomous and cooperative units connected via various communication channels across all levels of the production system—from individual machines and processes to entire manufacturing and logistics networks. Their capability to be modeled and managed in real time enables the effective execution of a wide range of tasks, including process control, dynamic adaptation, and the optimization of resources and flows. A generic model of a CPPS is presented in Fig. 4.

According to Monostori et al. [28], three fundamental characteristics define CPPS:

- Intelligence – the ability of individual elements to perceive and interpret their environment;
- Connectivity – the capacity for collaboration among devices and humans via the internet;
- Responsiveness – the capability to rapidly adapt to both internal and external changes.

The development of CPPS is also influenced by broader sociological dimensions, as highlighted by Morosini et al. [29], particularly in the context of collaborative networks and the evolving role of humans in technologically advanced manufacturing environments. These perspectives are essential for understanding the future of production systems, which will be not only technically sophisticated but also socially complex and inclusive [21]. The evolutionary shift from rigidly structured production lines to self-organizing and adaptive networks is also confirmed by recent scientific literature [30], which initiates discussions on new paradigmatic approaches in industrial manufacturing.

The integration of CPPS is a fundamental building block of Smart Manufacturing, which lies at the core of the digital transformation of modern factories. Smart Manufacturing is based on digital connectivity, where production systems are interconnected with databases, information systems, and user platforms, enabling end-to-end transparency and system-wide optimization.

Within this framework, CPPS facilitate autonomous coordination of production tasks, adaptive manufacturing aligned with market demand, energy efficiency, and rapid responsiveness to disruptions. By leveraging digital twins, machine learning, and advanced analytics, CPPS in smart factories are capable of predicting failures, optimizing maintenance, and even contributing to product development.

Beyond their technical advantages, CPPS also enable more efficient resource management, waste reduction, and improved traceability of materials and processes. The smart factories of the future will thus not only be technologically advanced but also highly responsive and adaptable. As noted by Morosini et al.[29], sociological dimensions are becoming increasingly critical for the successful deployment of these systems, as the transition toward smart manufacturing necessitates changes in organizational culture and mindset.

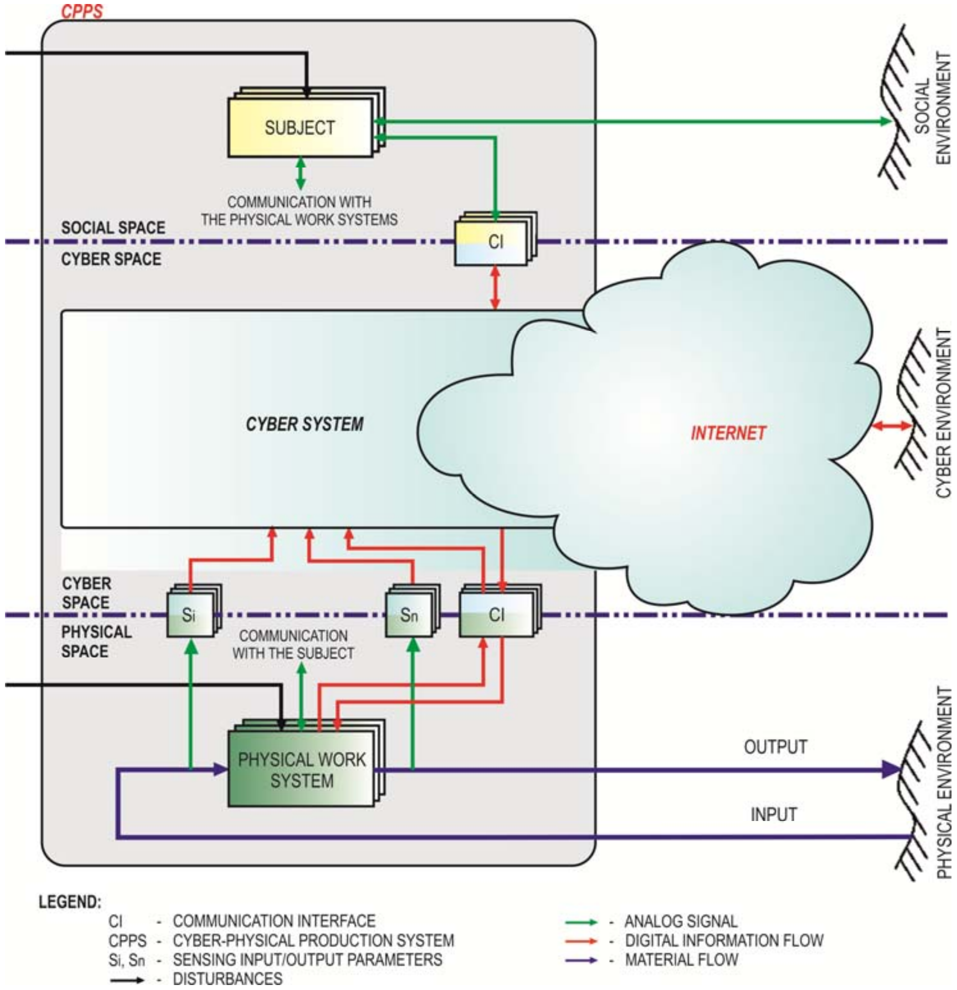

Figure 4. The Cyber-Physical Production System Model

In conclusion, CPPS are not merely a technical component of future manufacturing systems—they represent the core of the transformation toward intelligent, adaptive, and efficient production. As enabling technologies continue to evolve, the role of CPPS in smart manufacturing will become even more prominent. Nevertheless, key challenges will persist, including connectivity, security, interoperability, and the integration of humans as active partners in the production process.

2.5. Advantages and Limitations of Industry 4.0

Industry 4.0 offers numerous advantages (Table 1), including increased productivity, optimization of manufacturing processes, greater production flexibility, and enhanced product quality enabled by the use of smart technologies, AI, and automation. A key benefit also lies in cost reduction, achieved through more efficient resource management, lower energy consumption, and improved product traceability. Furthermore, digitalization and the implementation of the IoT allow for real-time monitoring of production indicators, thereby enhancing responsiveness to fluctuations in demand and market conditions.

Table 1: Advantages and Challenges of Industry 4.0

Advantages	**Limitations / Challenges**
Increased productivity and efficiency	High initial investment costs
Flexibility of production processes	Complex integration of technologies into existing systems
Improved product quality and traceability	Shortage of digital competencies and skilled workforce
Real-time data monitoring	Increased risk of cyberattacks
Possibility of customized production	Incompatibility of solutions, lack of standardization
Optimization of energy and resource consumption	Negative impact on certain job categories
Enhanced global competitiveness	Need for continuous adaptation to regulatory and security requirements

Despite its numerous advantages, the implementation of Industry 4.0 also presents certain limitations and challenges. Among the most significant are the high initial investment costs, often associated with the upgrade of existing infrastructure, the acquisition of new equipment, and the training of personnel. The complexity of integrating emerging technologies into legacy systems requires comprehensive planning and often demands a reorganization of operational workflows. Additionally, challenges related to cybersecurity and data protection arise, as increased digital connectivity also entails greater exposure to potential risks.

An additional challenge is the shortage of adequately skilled personnel. The transition to digital manufacturing requires new competencies in areas such as data analytics, programming, smart system maintenance, and a solid understanding of artificial intelligence concepts. Consequently, companies must invest not only in technology but also in the continuous education and development of human capital.

In the domain of standardization and interoperability, the diversity of solutions—which are often not mutually compatible—poses a significant barrier. This highlights the growing necessity for the adoption of uniform protocols, reference architectures, and open standards to facilitate seamless integration across systems and vendors.

Another important consideration is the impact on employment. While Industry 4.0 creates new technology-oriented jobs, it simultaneously reduces the demand for routine and low-skilled labor. This shift requires a strategic approach to issues of social equity, labor market restructuring, and the integration of digital literacy into all levels of education.

Industry 4.0 offers tremendous potential for advancing manufacturing enterprises; however, its successful realization is not guaranteed. Effective implementation requires a holistic and strategic approach that encompasses technological advancement, organizational transformation, employee training, and risk management. Only by addressing these dimensions can companies fully capitalize on the benefits of Industry 4.0 and ensure long-term sustainable growth.

3. Industry 5.0

3.1. Personalization

Industry 5.0 builds upon the digitalized and automated environment of Industry 4.0 by reintegrating the human as an active collaborator in the production process. In this context, personalization emerges as a core concept, enabling the transition from mass production to production tailored to the individual, often referred to as mass individualization.

Unlike mass customization, which offers a limited set of configurable options, personalization in the Industry 5.0 paradigm entails the active co-creation of the product by the end user. The customer becomes an integral part of the production chain, often participating as early as the design phase—enabled by technologies such as digital twins, augmented reality (AR), and open-architecture product systems (OAP). Examples of such practices include configurable furniture, custom automotive interiors, and personalized medical devices, all of which are tailored precisely to the user's individual needs.

This approach requires a high degree of interdisciplinary integration among information systems (e.g., CPPS), artificial intelligence, reconfigurable manufacturing systems (RMS), and human creativity. Co-creation platforms play a vital role by enabling users to visualize, select, and modify product functionalities, while smart factory processes dynamically adapt in the background to accommodate these changes.

The value of personalization within the Industry 5.0 framework lies not only in its economic impact—such as increased added value and stronger customer loyalty—but also in its sustainability dimension. By reducing unnecessary production, minimizing inventory, and better aligning supply with actual user needs, personalization significantly contributes to environmental efficiency.

Nevertheless, personalized production also introduces several challenges, including the complexity of planning, high demands on data and manufacturing infrastructure, and the need for systems capable of rapidly switching between varying specifications. However, it is precisely these complexities that reflect the core philosophy of Industry 5.0—a shift toward human-centricity, collaboration, and sustainability.

3.2. Cognitization in Manufacturing

Since the early 20th century, the development of manufacturing processes has been driven by the introduction of innovative approaches and technologies. The first major breakthrough occurred in 1913 with the implementation of the moving assembly line designed by Henry Ford, which fundamentally transformed not only the automobile manufacturing process but also the entire social structure. In the contemporary era, we are once again witnessing a manufacturing revolution, this time driven by the emergence of cognitive technologies as a central element.

Cognitive manufacturing is based on technologies that emulate human cognitive abilities such as learning, reasoning, understanding, and interaction. These systems enable the efficient analysis and interpretation of large volumes of data, surpassing the capabilities of traditional analytical approaches. The main advantages of cognitive technologies lie in their ability to continuously learn and improve, which directly contributes to increased productivity and enhanced product quality.

In manufacturing environments, cognitive technologies enhance human-machine interaction and enable real-time process monitoring. An illustrative example is IBM’s Watson Internet of Things (IoT) solution, which employs high-resolution cameras to detect defects on assembly lines. Such systems significantly reduce the time required for visual inspection and decrease the number of production errors. Early results demonstrate an approximate 80% reduction in inspection time and a 7–10% decrease in defects, underscoring the practical value of cognitive solutions in industrial quality control.

In the future, cognitive systems are expected to possess the capability not only to identify and predict problems, but also to autonomously implement corrective actions. Although this level of automation has not yet been fully realized, cognitive technologies are already transforming manufacturing processes and opening new opportunities for advancing production towards greater efficiency, quality, and flexibility.

Cognitive machines represent specific technological solutions built upon foundational technologies such as machine learning, natural language processing, and image recognition, as well as infrastructures like cloud computing, the IoT, and Big Data analytics. These technologies support the development of innovative systems that go beyond traditional passive technologies, demonstrating capabilities characteristic of higher-order cognitive processes, including learning, understanding, decision-making, problem-solving, planning, and pattern recognition. Recent studies indicate that the deployment of such technologies can lead to productivity gains of up to 40%.

Cognitive systems, or machines, operate through two fundamental phases: training and application. In the training phase, systems acquire essential skills and capabilities by analyzing large datasets. A well-known example is AlphaGo, a Go-playing program trained on millions of game moves. In the application phase, cognitive systems continuously refine their performance by adapting to users and specific contextual environments. Examples include the Nest smart thermostat and Amazon Echo smart speaker, both of which learn user preferences and habits over time to improve their functionality.

An important concept introduced by cognitive machines is *fleet learning*, whereby data collected from an entire fleet of devices is used to improve the software performance of all units simultaneously. A prominent example is Tesla, which continuously enhances the capabilities of its autopilot systems by leveraging data gathered from its entire vehicle fleet.

Cognitive machines also facilitate enhanced customer understanding and interaction through natural language processing and affective computing technologies, which enable systems to detect and interpret users' emotional states. Notable examples include the Apple Siri and Amazon Alexa digital assistants, which are becoming increasingly sophisticated in understanding conversational context and user emotions.

Cognitive machine technologies also hold significant potential for the development of predictive enterprises, where real-time data analysis enables the anticipation of needs, preventive actions, and increased operational efficiency. Applications such as predictive maintenance, predictive logistics, and similar strategies represent key advantages that cognitive machines bring to industrial environments.

Looking ahead, we can expect an even greater integration of humans and cognitive machines in the workplace, where these systems will augment human capabilities and automate routine tasks, while humans will focus on activities that require creative thinking and intuitive decision-making.

3.3. Enabling Technologies of Industry 5.0

As previously mentioned, Industry 5.0 represents the next evolutionary stage of manufacturing systems, shifting away from the paradigm of full automation toward human-centric, resilient, and sustainable production, see Fig. 1. The realization of these objectives relies on a set of keys enabling technologies that support human-machine integration, intelligent decision-making, and advanced digital infrastructure. The following sections present the most important technologies that enable the implementation and functioning of Industry 5.0.

Big Data analytics technologies enable the processing of complex and heterogeneous datasets in real time. This supports faster and more informed decision-making, the optimization of pricing strategies, and more accurate demand forecasting. Big Data plays a crucial role in product and service personalization, as it allows for a deeper understanding of individual user needs, see Fig. 5.

Edge computing reduces latency, enhances cybersecurity, and lowers storage costs. In the context of Industry 5.0, it facilitates direct interaction with devices in manufacturing environments and increases the reliability of systems.

Artificial Intelligence (AI) enables intelligent automation, quality control, rapid anomaly detection, and decision-making optimization. AI is the foundation of cognitive machines and supports the creation of production systems that learn, adapt, and suggest actions without the need for constant human intervention.

Cobots (collaborative robots) facilitate safe collaboration between humans and machines. They contribute to increased productivity, accuracy, and robustness of manufacturing tasks, particularly in repetitive and physically demanding operations. Their role in Industry 5.0 is especially significant, as they enable complementary collaboration, rather than simply replacing human workers.

Next-generation connectivity (6G) enables ultra-low latency, high reliability, and efficient resource management. In smart factories, these technologies will ensure high data throughput and support complex real-time applications, such as distribution algorithms, digital twins, and rapid response systems.

Digital twins are virtual replicas of physical systems and devices, allowing for monitoring, simulation, and process optimization. They are used to reduce costs, predict failures, customize products, and optimize maintenance. Digital twins serve as a fundamental tool for adaptive, data-driven manufacturing in the future.

Blockchain technology enables secure decentralized data management, the creation of digital identities, and transaction transparency. In the context of Industry 5.0, it provides traceability, protects intellectual property, and fosters decentralized collaboration within value chains.

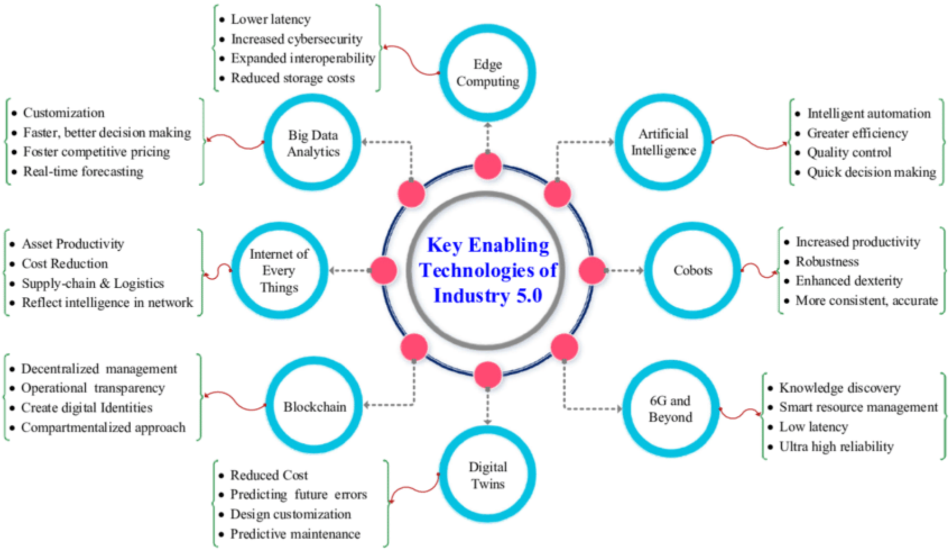

Figure 5. KeysEnabling Technologies of Industry 5.0

Internet of Everything (IoET) extends the concept of the Internet of Things (IoT) to include all types of intelligent devices and systems. It increases productivity, reduces costs, and enables intelligent logistics and supply chain management. Within Industry 5.0, IoET integrates with AI and digital twins to create dynamic, self-regulating environments.

3.4. Cognitive Cyber-Physical Production Systems

Cognitive Cyber-Physical Production Systems (C-CPPS)[3], [2] represent a key building block of the new manufacturing paradigm known as Adaptive Cognitive Manufacturing Systems (ACMS)[31], [32], which is closely linked to the concept of the fifth industrial revolution – Industry 5.0. This represents the next evolutionary stage of traditional Cyber-Physical Production Systems (CPPS)[28], [7], enhanced by the integration of cognitive technologies and artificial intelligence that enable a higher level of adaptability, learning, and collaboration between humans and machines.
At their core, C-CPPS combine intelligent algorithms, artificial intelligence, and sensing technologies to execute digitalized and cyber-physical functions. As described by Hozdić and Makovec [3], digitalized functions refer to the automation of information processes, while cyber-physical functions integrate both analog and digital mechanisms in the physical world with control in the cyber space. C-CPPS enhance these functionalities by adding capabilities such as sensing, prediction, self-adaptation, and intelligent decision-making.

The design of the C-CPPS is based on a multi-layered architecture of a multi-agent model, which enables distributed control of manufacturing systems, see Fig 6. The three-tiered structure includes the operational level, the coordination level, and the decision-making level. Each of these levels incorporates intelligent agents that communicate with both the physical and social environments. This means that physical elements (e.g., machines, actuators) send data to the digital space via sensors and communication interfaces, where they are processed by cognitive agents.

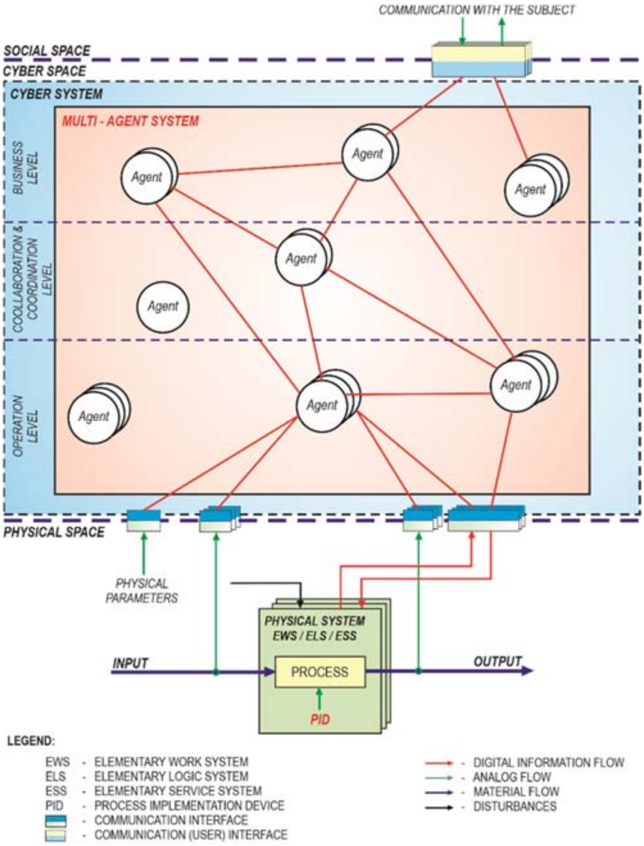

Figure 6. The Cognitive Cyber-Physical Production System Model[3]

These agents, based on advanced AI solutions, are capable of performing complex tasks such as predicting failures, optimizing workflows, detecting anomalies, and real-time decision-making. They can also learn from past events (referred to as fleet learning), which allows them to continuously improve the system's overall efficiency. An important aspect of this design is the inclusion of the human operator—through user interfaces, the operator can influence the system in real time, while also receiving enriched information to support decision-making.

C-CPPS form the foundation for the smart factories of the future, enabling complete synergy between the digital, physical, and social environments. Compared to previous systems, these systems are more flexible, intelligent, and responsive. Their integration facilitates a high degree of production customization, supports sustainability goals, and strengthens the role of the human as a co-creator in the manufacturing process.

As the authors conclude, C-CPPS are not just a continuation of existing technological trends but a breakthrough point in the development of manufacturing systems, enabling the transition to Industry 5.0—an era where technology does not replace humans but instead supports, augments, and empowers them to have greater creative freedom in value co-creation.

The significance of cognitive manufacturing systems also lies in their ability to co-decide with humans, where the human does not lose control but becomes an integral part of the intelligent ecosystem. In this way, the gap between full automation and human involvement is bridged, which is the central goal of Industry 5.0—to restore the balance between technological efficiency and human creativity.

Due to their advanced architecture and high level of intelligent behavior, C-CPPS are well-suited for environments that require high levels of personalization, agility, and resilience. Their development and integration represent a significant step towards realizing the vision of future manufacturing, where systems are not only digital and automated but also intelligent, adaptive, and deeply connected with the user experience.

3.5. Advantages and Limitations of Industry 4.0

Industry 5.0 introduces a new paradigm that goes beyond the technological focus of Industry 4.0, placing the human back at the center of production systems. Its goal is not only increased automation and efficiency, but primarily the creation of human-centric, sustainable, and resilient systems. The advantages of this paradigm are diverse and manifest at the technical, social, and environmental levels (Table 2).

One of the key benefits of Industry 5.0 is production personalization, which enables the creation of customized products tailored to individual user needs. In contrast to mass customization from the previous industrial paradigm, Industry 5.0 encourages active user participation in the product design phase. This increases the added value of products, strengthens customer loyalty, and reduces waste, leading to a more sustainable production process. Digital twins, co-creation platforms, and reconfigurable manufacturing systems are essential tools that enable this flexibility and responsiveness.

Furthermore, Industry 5.0 facilitates the deep integration of cognitive technologies, such as artificial intelligence, natural language processing, fleet learning, and Big Data analytics. These systems do not merely analyze but also learn, adapt, and make autonomous decisions.

Table 2: Advantages and Challenges of Industry 5.0

Advantages	Limitations / Challenges
Personalized production with user collaboration	High complexity of design and management
Strengthening the role of humans in production processes	High skill requirements for the workforce
Increased quality and reliability due to cognitive systems	Need for secure, decentralized data infrastructure
Greater sustainability and waste reduction	High costs for implementing advanced technologies and architecture
Intelligent automation and real-time learning	Ethical concerns regarding decision-making algorithms
Enhanced competitiveness with high added value	Unclear standardization and lack of global interoperable solutions

On a social level, Industry 5.0 contributes to the empowerment of workers, as technologies do not replace humans but rather complement them. The focus is on collaboration with cobots, intuitive user interfaces, and affective computing, which detects the emotional states of users. This improves work ergonomics, job satisfaction, and the role of the human as both creator and decision-maker.

Despite its many advantages, the implementation of Industry 5.0 is not without challenges. One of the key challenges is the high complexity of system integration, as personalized and cognitive manufacturing requires a highly modular and interoperable infrastructure. Furthermore, there is a need for an advanced data architecture capable of rapid and secure data processing, which increases the importance of edge computing and blockchain for decentralized information management.

Industry 5.0 represents a shift from technological efficiency to technology-supported human creativity. By fostering collaboration between humans and machines, intelligent decision-making, and a sustainable approach, it opens up new development horizons for manufacturing. However, its success depends not only on technology but also on systemic understanding, collaboration, and the adaptability of organizations. Only through these elements can its potential be realized in creating a more inclusive, responsible, and efficient manufacturing future.

A significant barrier remains the shortage of adequately trained personnel. The new generation of manufacturing systems requires experts in areas such as artificial intelligence, data science, ergonomics, and user experience design. Employee training and organizational culture transformation have become crucial elements for success. Additionally, ethical concerns related to automated decision-making and the transparency of algorithms present another critical challenge.

4.Comparison of Key Characteristics of Industry 4.0 and Industry 5.0

Industry 4.0 represents the transition to the digitalization of manufacturing processes, utilizing advanced technologies such as CPS, IoT, cloud computing, and AI. The primary focus is the establishment of smart factories, where autonomous systems with the ability to communicate with one another enable efficient automation, increased productivity, and the optimization of overall business processes.

At the onset of Industry 4.0, the role of humans was uncertain, as automation began to take over many tasks previously handled by humans. This raised concerns regarding the future of jobs and the quality of decision-making in the workforce.

In contrast, Industry 5.0 places humans, social responsibility, and sustainable development at the forefront. This paradigm emphasizes the importance of reintegrating humans into manufacturing processes and fostering greater system resilience. Several global challenges, such as climate change, pandemic crises, and geopolitical tensions, have highlighted the need for greater human involvement in organizational decision-making. Industry 5.0 promotes a collaborative approach, where robots and artificial intelligence systems work in partnership with humans, not as competitors, but as assistants and co-creators.

The key differences between the Industry 4.0 and Industry 5.0 paradigms are summarized in Table 3.

Despite the clear differences between the automation-driven approach of Industry 4.0 and the human-centric approach of Industry 5.0, both concepts often complement each other in practice. Researchers therefore propose an integrated hybrid model that combines the strengths of both paradigms. This model relies on the use of digital cognitive clones, which replicate human decision-making processes and enable effective interaction between humans and automated systems. By doing so, it combines the efficiency of automation, characteristic of Industry 4.0, with the social responsibility and sustainability emphasized by Industry 5.0. Such an integrated approach can create a new generation of adaptive, smart, and resilient manufacturing systems, capable of effectively responding to rapid changes in the global environment.

Table 3: Comparison between the Industry 4.0 and Industry 5.0

Feature	Industry 4.0	Industry 5.0
Main Focus	Automation, efficiency, digitalization	Human-centricity, collaboration, sustainability
Role of Humans	Replaced by technology	Partner collaborating with technology
Type of Production	Mass customization	Mass individualization
Key Technologies	IoT, Big Data, AI, CPPS, ERP, MES, SCADA	Cognitive machines, cobots, digital twins, blockchain, IoET
Decision-Making Approach	Automated, algorithmic	Co-decision by humans and machines
Goals	Increased productivity, flexibility	Sustainability, resilience, human value
Challenges	Security, interoperability, costs	Ethical dilemmas, complexity, skilled workforce

Industry 5.0 does not discard the technological achievements of the previous paradigm, but rather builds upon them, with a focus on responsible development, human inclusion, and care for future generations. This represents a new phase in the industrial revolution, where technology does not replace humans, but instead supports and enhances human creativity.

5. Technological Challenges and Opportunities

5.1. Implementing AI in Manufacturing

Artificial Intelligence (AI) in the manufacturing sector represents one of the key technological advancements of the past decade. Its implementation enables manufacturing companies to achieve greater efficiency, accuracy, and flexibility in production processes. Key applications of AI include optimization of production lines, predictive maintenance, supply chain management, and the improvement of final product quality.

Despite its numerous advantages, there are also significant technical and organizational challenges that companies face when implementing AI. Among the biggest obstacles are high initial investment costs, the need for substantial changes to existing manufacturing infrastructure, and the lack of specialized expertise for the development, implementation, and maintenance of AI solutions. Additionally, the implementation of advanced algorithms requires careful integration with the human factor in production processes, where it is crucial to maintain a clear role for humans in decision-making processes. Research shows that despite these challenges, AI can significantly increase the competitiveness of companies, making its strategic importance in modern manufacturing invaluable.

5.2. The Impact of Industry 5.0 on Sustainable Development

Industry 5.0 emphasizes the shift from fully automated and digitalized systems to a more balanced approach, where technologies are integrated with human values and sustainable development goals. This paradigm is not solely focused on technological advancement, but also on social and environmental responsibility. At the heart of this approach is the reintegration of humans into the production process, aimed at achieving greater resilience, sustainable development, and ecological responsibility.

Technological innovations within Industry 5.0, such as digital twins, collaborative robots, and smart circular products, enable more efficient resource use and reduce environmental impact. Recent research also highlights that the human-centric approach leads to improved resilience of companies to global crises and greater social acceptance of new technologies. As a result, Industry 5.0 is not just a technological shift, but also an important social step toward a sustainable future.

5.3. Security and Ethical Aspects of Human-Machine Interaction

With the increasing integration of cognitive technologies and artificial intelligence (AI) into manufacturing processes, the interaction between humans and machines is becoming increasingly complex and sensitive. Industry 5.0, which aims to establish human-centric production environments, also raises numerous security and ethical questions related to co-decision-making, control, and trust between users and machine systems.

Cybersecurity remains one of the key areas of risk. The growing connectivity of systems through the Internet of Things (IoT, IoET) and the use of digital twins expose systems to a higher risk of malicious intrusions, data manipulation, and cyber sabotage. Ensuring the integrity, confidentiality, and availability of data has become strategically crucial, as security incidents not only affect the technological infrastructure but also user trust in new solutions.

On the ethical level, key concerns include the transparency of AI decision-making and accountability for mistakes. The use of self-learning algorithms (e.g., in quality control or production planning) raises the dilemma: who is responsible for the decision—the machine, the developer, or the operator? In parallel, there is a growing need for Explainable AI (XAI), which provides understandable justifications for decisions, a crucial aspect for maintaining human oversight and trust.

Furthermore, the affective dimension of interaction is important, particularly in collaboration with cobots and systems that detect user emotions. The ethics of such interactions include issues related to manipulation, privacy, and the appropriate boundaries between humans and machines. Improper implementation can lead to an over-reliance on technology and a diminished critical judgment from users.

Industry 5.0 thus requires a holistic approach to designing human-machine interactions, which includes:

- security protocols and protective mechanisms against misuse,
- transparent algorithms and decision-explanation mechanisms,
- respect for privacy and human dignity, and
- a clear distinction of roles between technology and users.

Adhering to these ethical and security principles contributes not only to greater societal acceptance of technologies but also to their long-term successful integration into the production environments of the future.

5.4. Technical and Organizational Barriers to the Transition to Industry 5.0

The transition to Industry 5.0 does not only represent a technical change, but also requires fundamental organizational adjustments and strategic change management. On the technical level, the biggest challenges include the integration of new technologies into existing systems, ensuring high levels of interoperability between different technologies, and securing robust cybersecurity.

In addition to these technical barriers, organizational obstacles also play a significant role, with notable challenges such as employee resistance to change, the need for extensive staff training, and the adaptation of organizational culture and work processes. Overcoming these challenges requires strategic planning, collaboration between departments, and effective communication between management and employees.

To successfully navigate these barriers, researchers recommend a gradual implementation of new technologies, proactive change management, and intensive stakeholder collaboration, all of which will facilitate the transition to Industry 5.0 and enable companies to achieve sustainable long-term growth and adaptability.

6. Future Trends

6.1. Applications of AI in Manufacturing Processes

The future of manufacturing will be largely shaped by the widespread use of artificial intelligence (AI), which is increasingly emerging as a key tool for optimizing industrial processes. One of the most promising applications of AI in the future is predictive analytics, where, based on large volumes of data, disruptions in production, machine wear, or product defects can be predicted before they occur. Additionally, the development of reinforcement learning approaches will enable systems to learn from everyday operations, thereby automatically improving their efficiency and decision-making.

In the future, artificial intelligence will significantly contribute to greater flexibility in production systems, enabling rapid adaptation to individualized customer demands and supporting the implementation of mass customization. Research predicts that AI will become a central element of self-adaptive and autonomous factories, where it will collaborate with robots, sensors, and digital twins to constantly monitor, learn, and optimize production in real-time.

6.2. Development of Smart Factories of the Future

The concept of smart factories will evolve into a more comprehensive and integrated form in the future, as technology will enable fully digitalized, connected, and self-organizing production systems. The smart factories of the future will not only be autonomous, but also predictive, responsive, and sustainable. Key characteristics will include digital twins, which will allow for the virtual simulation of the entire production process, IoT infrastructure that will ensure continuous data monitoring, and the use of AI for decentralized decision-making.

These factories will operate as cyber-physical systems, capable of real-time adaptation to changes in the environment or demand. Furthermore, future smart factories will increasingly focus on energy efficiency, waste minimization, and renewable energy sources, aligning with global sustainable development goals. In such an environment, digital infrastructure will be crucial for creating value and ensuring rapid responsiveness to market changes.

6.3. The Role of Humans in Future Manufacturing Systems

Although technology is advancing at an incredible pace, the role of humans in future manufacturing systems will not be diminished, but rather transformed[3], see Fig 7. Within the framework of Industry 5.0, the importance of a human-centric approach is already emphasized, and this will become even more crucial in the future. Instead of technology completely replacing humans, the human factor will become a key complement to artificial intelligence, particularly in the context of creativity, decision-making in complex situations, and ethical and strategic judgments.

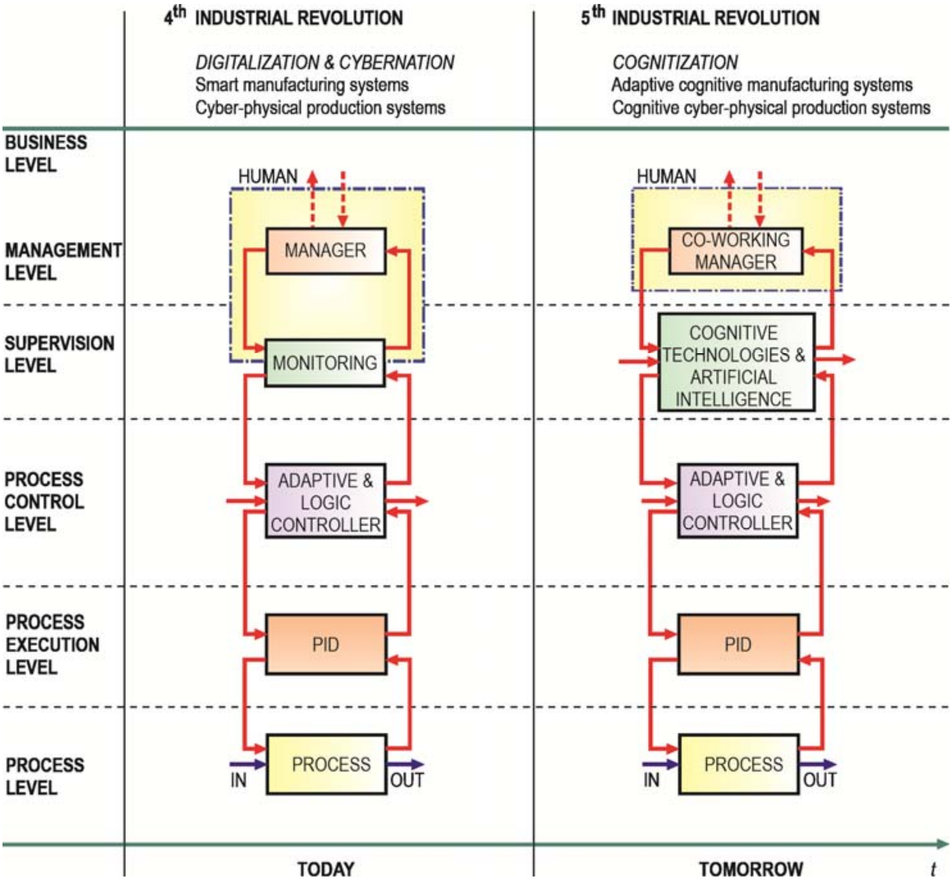

Figure 7. Transition of the human's role from Industry 4.0 to Industry 5.0.

Future manufacturing systems will include human-in-the-loop models, where humans will be actively involved in monitoring, improvements, and decision-making within automated environments. Furthermore, the focus will be on ergonomics, psychological well-being of employees, and job quality, meaning that manufacturing technologies will be adapted to humans, rather than the other way around. The role of education and continuous training will be especially important, as employees will need to develop new digital and analytical competencies in order to effectively collaborate with smart systems.

7. Conclusion

Industrial development in the 21st century has been marked by two paradigmatic shifts: first, with the digital and automated revolution, known as Industry 4.0, followed by the rise of Industry 5.0, which once again places humans at the forefront as a key component of manufacturing systems. The analysis of both approaches reveals that technological progress is increasingly focused on creating intelligent, sustainable, and human-centric manufacturing environments. Industry 4.0 is based on automation, digitalization, and the use of advanced information systems, such as IoT, AI, digital twins, and CPPS, enabling the optimization of manufacturing processes, increased efficiency, and connectivity. However, it faces challenges such as high investment costs, complex integration, and the lack of standardization.

Industry 5.0 builds on these foundations by placing humans at the center of the manufacturing system. Key elements include product personalization, the use of artificial intelligence to support decision-making, collaboration with cobots, and an overarching sustainability focus. This shift is not only about technological development but also about a societal and organizational change, requiring a high level of interdisciplinary collaboration, ethical judgment, and the creation of an inclusive work environment.

Technological challenges such as security, interoperability, and organizational culture change are significant factors in the transition to Industry 5.0. However, these challenges also present opportunities—such as the creation of smart factories of the future, where production processes can be monitored and adapted in real-time, and the development of new human-machine interactions, where technology complements human capabilities rather than replacing them.

Looking to the future, artificial intelligence, smart algorithms, digital twins, and advanced robotics will become the standard in manufacturing. At the same time, the importance of human creativity, adaptability, and ethical decision-making will continue to grow. The success of future industrial systems will therefore rely on a balance between technological capability and human values.

Industry 5.0 not only represents a new stage of development but also an opportunity for a holistic transformation of manufacturing towards a sustainable, inclusive, and responsible future.

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