

Article

Evolution of the Human Role in Manufacturing Systems: On the Route from Digitalization and Cybernation to Cognitization

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Abstract: Modern society is living at a time of revolutionary changes in all areas of human life. For example, the field of industrial manufacturing has greatly influenced the role of human beings during the past 30 years. Modern manufacturing systems are in a phase of transition, in accordance with the concept of the fourth industrial revolution (Industry 4.0). A new manufacturing paradigm based on the principles of Industry 4.0 is presented by Smart Manufacturing Systems (SMS). A basic building block of SMS is cyber-physical production systems (CPPS), which together with innovative-management principles of emergence, self-organization, learning, open innovation, collaboration and the networking of people and organizations are the key principles of Industry 4.0. The three key enablers of Industry 4.0, i.e., the connectivity, the digitization and the cybernation of work processes in manufacturing systems, have paved the way for a new industrial revolution, i.e., Industry 5.0 concept that is bringing about a new paradigm in the field of manufacturing systems, the so-called Adaptive Cognitive Manufacturing Systems (ACMS). A fundamental building block of ACMS is the new generation of manufacturing systems called Cognitive Cyber-Physical Production Systems (C-CPPS), which are based on CPPS concepts and incorporate cognitive technologies and artificial intelligence. This paper presents the revolutionary development of manufacturing and manufacturing systems through the industrial revolutions and the evolution of the role of humans in manufacturing systems towards Industry 5.0.

Keywords: cybernation; cognitization; digitalization; human role; adaptive cognitive manufacturing systems; cognitive cyber-physical production system; Industry 4.0; Industry 5.0



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1. Introduction

Industry is the most important driver of economic development [1]. In the last decade, European and global industry have been in an era of digitalization and cybernetics. Manufacturing companies are striving to adapt their production structures and systems to the principles of Industry 4.0 [2].

The key enablers of Industry 4.0, such as decentralization, connectivity, horizontal and vertical integration, collaboration, digitalization, cybernation, smart machines and products, and automation [2], have revolutionized the industrial sector. These elements have opened the way to new forms of organization and innovative management principles. The new organization forms and the innovative management principles have become key elements of Industry 4.0 manufacturing systems [3], the so-called Smart Manufacturing Systems (SMS) [4].

These SMS enable the processes of digitalization and cybernation, thus reducing human intervention in the manufacturing process. Over time, various concepts of SMS and advanced automation technologies have been developed, such as cyber-physical production systems (CPPS) [5], cloud manufacturing [6], ubiquitous manufacturing systems [7], socio-cyber-physical systems (SCPS) [8], socio-cyber-physical manufacturing systems (SCPMS) [9], intelligent manufacturing [10], and personalized manufacturing [11].

The key technologies of Industry 4.0 and SMS are important to European industry, but the Severe Acute Respiratory Syndrome Coronavirus Type 2 (SARS-CoV-2) has caused many problems for the economy, industry, manufacturing activities, transport, etc. In fact, the SARS-CoV-2 pandemic [12] highlighted the need to rethink existing working methods and approaches in European and global industry. The pandemic has shown industries all around the world that their current manufacturing systems are not as resilient as was assumed [13]. According to a literature review [14–17] many authors have pointed out the problems that manufacturing companies around the world have had due to the SARS-CoV-2 pandemic. Modern industry, manufacturing companies and their manufacturing systems must be focused on agile, networked, service-oriented, green, and social manufacturing practices, among others [18]; be more environmentally, socially, and economically sustainable and human-centred [19,20]; and be resilient [13,21].

The future of production systems will depend on socio-technical developments and business strategies shaped by global changes [19]. The evolution and the future of manufacturing and manufacturing systems are presented in [19,20,22,23].

Earlier concepts of manufacturing systems including the latest CPPS tend to underestimate, neglect or ignore the role of humans in manufacturing. The importance of the role of humans in manufacturing systems of the future is acknowledged in [8,9,24,25]. This role was also highlighted during the pandemic.

The paper [25] emphasizes the need to restructure manufacturing systems from the perspective of social factors. According to [19], humans are an integral part of manufacturing systems and play an important role in their management and control.

In [2] the authors highlight that in structuring new production systems, physical, cyber, and social systems come together to achieve common goals and create intelligent environments. In the future, the agility, efficiency, flexibility, and robustness of such systems will generally depend on the roles of the humans in them.

Based on a literature review, this paper presents the evolution of the role of humans in manufacturing systems in the spirit of digitalization, cybernation and cognitization. Definitions of digitalization, cybernation and cognitization in manufacturing systems are established. The main contribution of this paper is a systematic presentation of the different roles of humans in manufacturing systems through the evolution of industrial revolutions and the new concept of the next generation of CPPS, called Cognitive Cyber-Physical Production Systems (C-CPPS). Finally, a new role for humans in the C-CPPS concept is presented.

New trends and changes in manufacturing industry, triggered by the consequences of the SARS-CoV-2 pandemic, are the motivation for this paper and have determined its scope. The structure of the paper is outlined below. Section 1 provides an insight into the literature on the topic of the article by analyzing data from scientific databases. Section 2 deals with the development processes of industrial revolutions and manufacturing paradigms as well as with the transformation of manufacturing systems in the light of the digitalization and cybernation of work processes. Manufacturing systems in the wake of industrial revolutions are defined and described, with special attention to modern, advanced cyber-physical production systems. The section concludes with a review of the literature in the field of artificial intelligence and cognitive technologies. Section 3 presents the changing role of humans through the development of manufacturing systems. It introduces the concept of C-CPPS as fundamental building blocks of the adaptive cognitive manufacturing systems paradigm. This section discusses the new role of humans in the manufacturing system during the transition of manufacturing industry from Industry 4.0 to the new industrial revolution, Industry 5.0. Finally, discussions, conclusions and future research opportunities are presented in Section 4.

Publications Trends and Bibliometric Analysis

This section presents an extensive literature analysis, which was conducted from a variety of perspectives. The number of scientific works that deal with the topic of the

human role in the manufacturing system and works that include the keywords of this paper are analyzed.

To review the relevant literature, we used the Scopus database, created by Elsevier and launched in 2004. According to [26], it contains information from about 11,678 publishers with 34,346 peer-reviewed journals in areas such as life sciences, social sciences, natural sciences, and health sciences. The database contains three types of sources: Book Series, Periodicals, and Journals. The journals included in Scopus are evaluated each year using four numerical quality measures, such as the h-index, CiteScore, SJR, and SNIP.

To find as many scientific papers as possible describing the role of humans in production systems, we first collected as many possible phrases that define the topic and appear in scientific papers. We also used the artificial intelligence chatbot ChatGPT to search for phrases. We reviewed the result and wrote queries to search the Scopus database of scientific articles, see Figures 1–6.

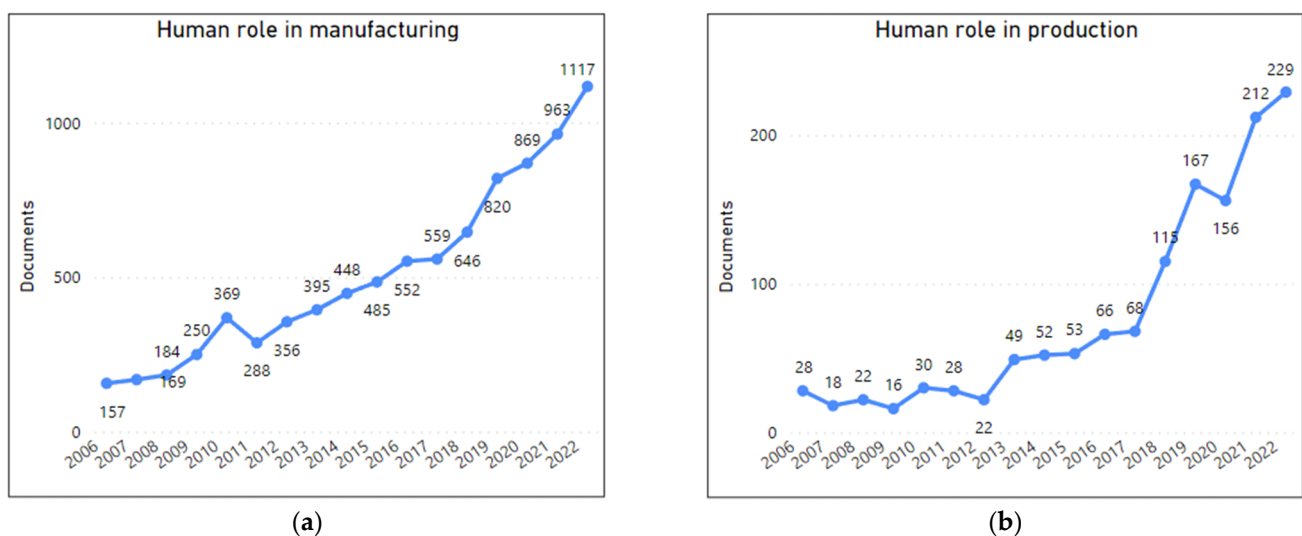


Figure 1. (a) Human/s role in manufacturing—years 2006–2022, 8627 documents in period, (b) Human/s role in production—years 2006–2022, 1331 documents in period.

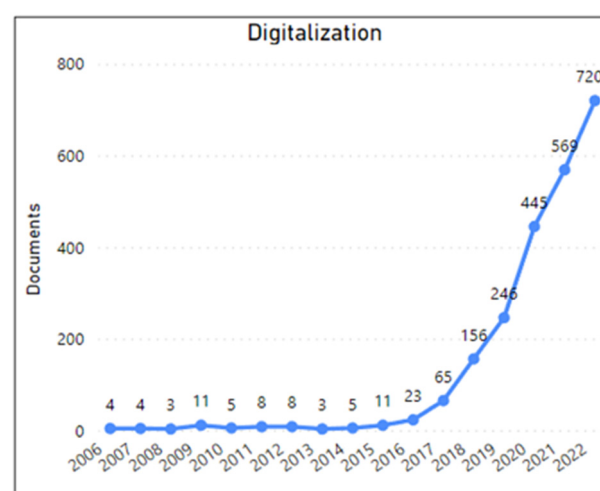


Figure 2. Digitalization—years 2006–2022, 2286 documents in period.

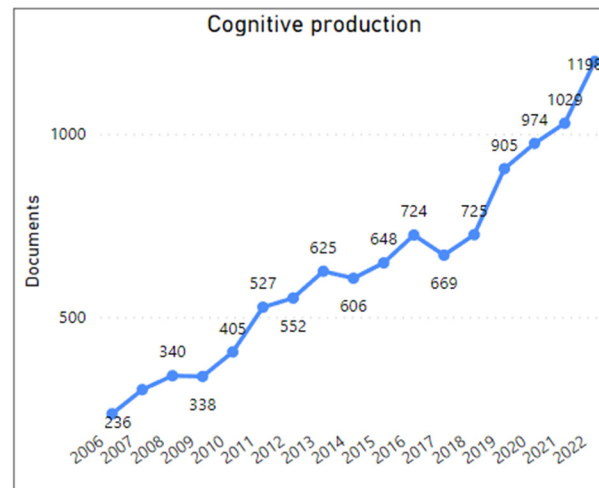


Figure 3. Cognitive manufacturing/production—years 2006–2022, 10,803 documents in period.

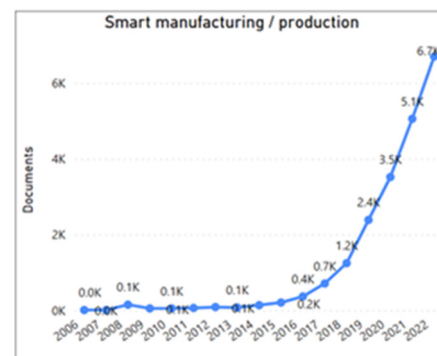


Figure 4. Smart manufacturing/production systems—years 2006–2022, 20,812 documents in period.

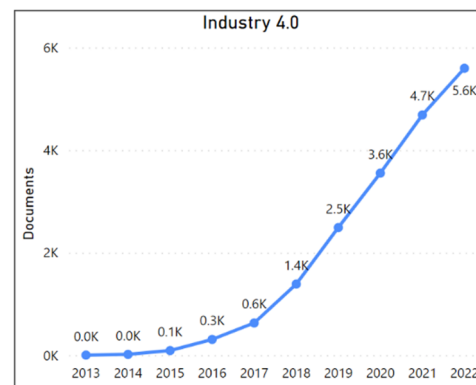


Figure 5. Industry 4.0—years 2006–2022. No data before 2012, 18,760 documents in period.

With graphs 1 (Human role in manufacturing) and 2 (Human role in production), we wanted to see the difference between whether the authors associated the human role more with manufacturing systems and processes or with production systems and processes. Manufacturing systems refer to the methods, processes, and equipment used to transform raw materials into finished products. This term often refers to mass production techniques and involves the use of specialized machinery and assembly lines. A broader field is covered by production systems, which refer to the overall organization and management of the process of producing goods and products. This includes planning, scheduling, materials management, quality control, and other aspects of the production process. The difference between the two graphs is obvious. The authors associated the human role with manufacturing in significantly more documents (8627) than with production (1331).

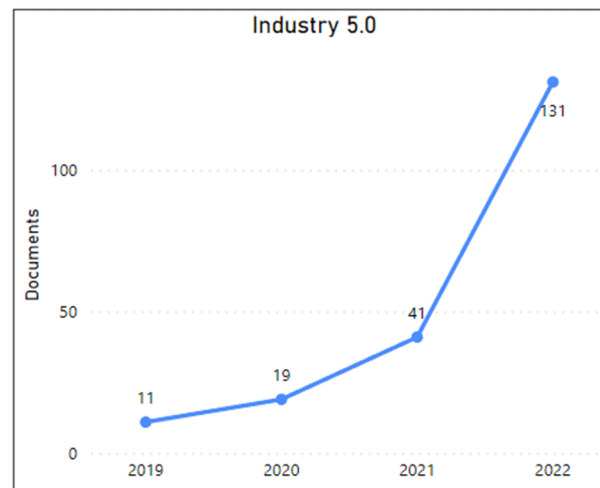


Figure 6. Industry 5.0—years 2006–2022. No data before 2019, 202 documents in period.

However, it can also be seen that the steepness of the curve in Figure 1a (Human role in manufacturing) and Figure 1b (Human role in production) has increased significantly and coincides with the change in the slope of the curves in Figure 2 (Digitalization), Figure 4 (Smart manufacturing/production) and Figure 5 (Industry 4.0). Therefore, it can be concluded that the authors have recognized the increased role of humans in digitization and smart manufacturing/production at the same time as they describe digitization and smart manufacturing/production.

2. Digitalization and Cybernation of Work Processes in Manufacturing Systems

2.1. Background

Industrial revolutions mark radical changes in the development of industry. These changes are characterized by certain achievements that influence both the direction of development of the entire industry as well as new system solutions in the structuring of production systems and the organization of work.

From the point of view of industrial production, the first important achievement is the discovery of steam-based machines, which served as a source of power for driving equipment, paving the way for the mechanization of industrial production and the construction of factories. This is referred to as the first industrial revolution (Industry 1.0), see Figure 7.

The development continued with new discoveries (e.g., direct and alternating current, light bulbs, power plants, transmission lines, internal combustion engines, telecommunications, etc.), which happened in the second half of the 19th century. Steam as an energy source in factories was replaced by electricity, gas and oil. This development led to the second industrial revolution (Industry 2.0), which is characterized by the following economic changes: an increasing spatial expansion of the economy; the expansion of world trade; the development of technologies for global trade that significantly reduced costs and increased the safety and efficiency of trade; the development of factory production systems based on scientific management principles; and the development of the principles of mass production in the automobile factories of Henry Ford. There is a significant market development that opens the possibility of producing a larger quantity of products for wider consumption on the principle of mass or serial production. One of the most important technologies of mass production is Ford's moving assembly line. Special manufacturing systems or Dedicated Manufacturing Lines (DML) have been developed for this type of production, where machines replace human labor.

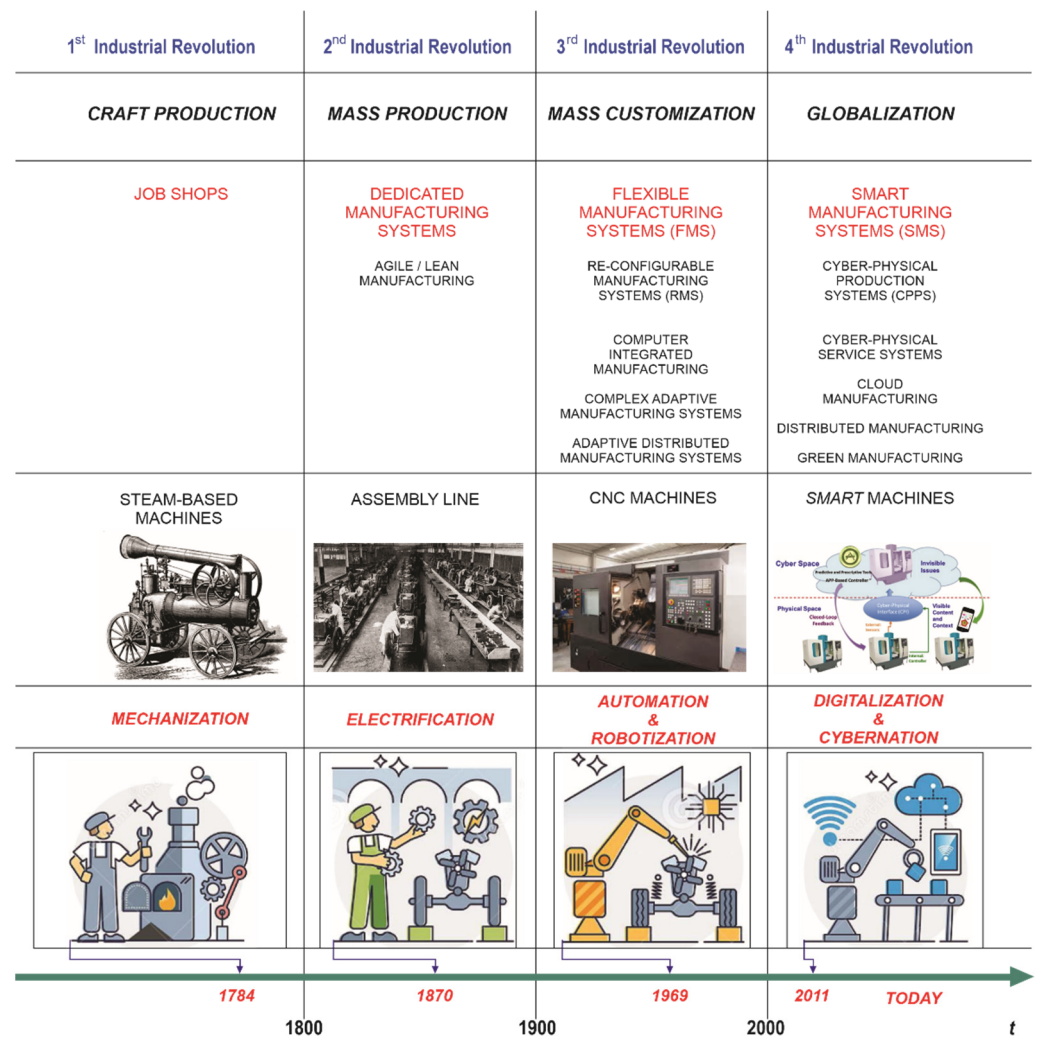


Figure 7. Timeline of Industrial Revolutions.

The third industrial revolution (Industry 3.0) began in the 1960s. This period marked important technological achievements in the field of information and communication sciences, electronics and computer science, and production automation. Industry 3.0 introduced electronics and digital technology into production. The fundamental characteristic of this period was the introduction of flexible manufacturing based on automation and robotization. In the period between 1980 and 2010, production became more flexible, which enabled the mass adaptation of products to the needs of individual customer groups (mass customization).

The fourth generation of industry (Industry 4.0) represents a continuation and upgrade of Industry 3.0. In parallel with the all-encompassing technological development—especially in the field of information and communication technologies (ICT)—industrial production has undergone profound changes in recent years. The last 20 years have seen important changes in the field of industrial production: state borders in relation to markets have disappeared, extensive globalization has taken hold, while supply and demand for industrial products are greater than ever before. Factories are increasingly responding to unpredictable external influences. The dimensions of Industry 4.0 are significantly larger than those of the earlier industrial revolutions [27].

In [28] Schwab points out that Industry 4.0 is characterized by the fusion of technologies from different fields such as genetics, nanotechnologies, renewable energy sources, and quantum computing, etc., and their interaction in different domains (physical, digital and

biological). According to [29], Industry 4.0 refers to the intelligent networking of machines and processes based on CPS and modern ICT.

Digitalization, cybernation [3] and advanced ICT have enabled the rapid expansion of digital and virtual enterprises and the development of global and distributed production. They have also contributed to the development of digital and virtual factories and smart manufacturing systems.

In the context of Industry 4.0, an environment is created that allows physical and virtual production systems to collaborate globally and flexibly, enabling the full customization of products and the creation of new business and production models [28]. Recently, many SMS models and concepts have been developed.

This section presented the evolutionary development of technology, business strategy, production paradigms, and production models during the period of the industrial revolutions. The next section describes production systems and the role of humans in production systems during industrial revolutions.

2.2. Description of Manufacturing Systems

In reviewing the literature, we found that the terms “production” and “manufacturing” have been used interchangeably.

The International Institution for Production Engineering Research (CIRP) has defined manufacturing as “... a series of interrelated activities and operations involving the design, material selection, planning, production, quality assurance, management and marketing of the products of the manufacturing industries.” [30].

According to CIRP, production is “... the act or process of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality” [30].

The term “manufacturing system” was first introduced by M. E. Merchant in his paper [31] in the 1960s. Merchant introduced the systems approach to manufacturing philosophy as an important conceptual tool for modeling and controlling objects in manufacturing at the macro level.

In [24,32] Peklenik defined a factory as a complex adaptive manufacturing system (CAMS) and introduced three levels of organization: (1) the corporate (decision-making) level, (2) the management level, and (3) the manufacturing level.

At the corporate level, business policy is set in terms of the type of products, the volume and the product mix, management, financing, location, profit targets, and so on. The management level comprises a set of agents and/or multiple agents, such as operations management, which are responsible for implementing the policy set by the board at the corporate level. The manufacturing level consists of a number of multiple agents required to transform an innovation or prototype into a marketable product.

In [24,32] Peklenik defined the elementary work system (EWS). An EWS is a basic building block of manufacturing systems at the manufacturing level and consists of the work process, the process implementation device (PID) and the Subject, in our case a human, see Figure 8.

Due to the increasing uncertainty in markets and the intense communication between elements of manufacturing systems, their behavior is becoming more complex and unpredictable, making them more difficult to manage. The elements of modern manufacturing systems are not only real, physical and social elements, but, there are also many digital and virtual or cyber elements. Such systems represent the generation of advanced manufacturing systems [25].

In an advanced manufacturing system, three systems are combined: a physical system, a cyber system, and a social system. Therefore, the emerging cyber-physical-based manufacturing systems are a logical and practical step in the evolution of manufacturing systems.

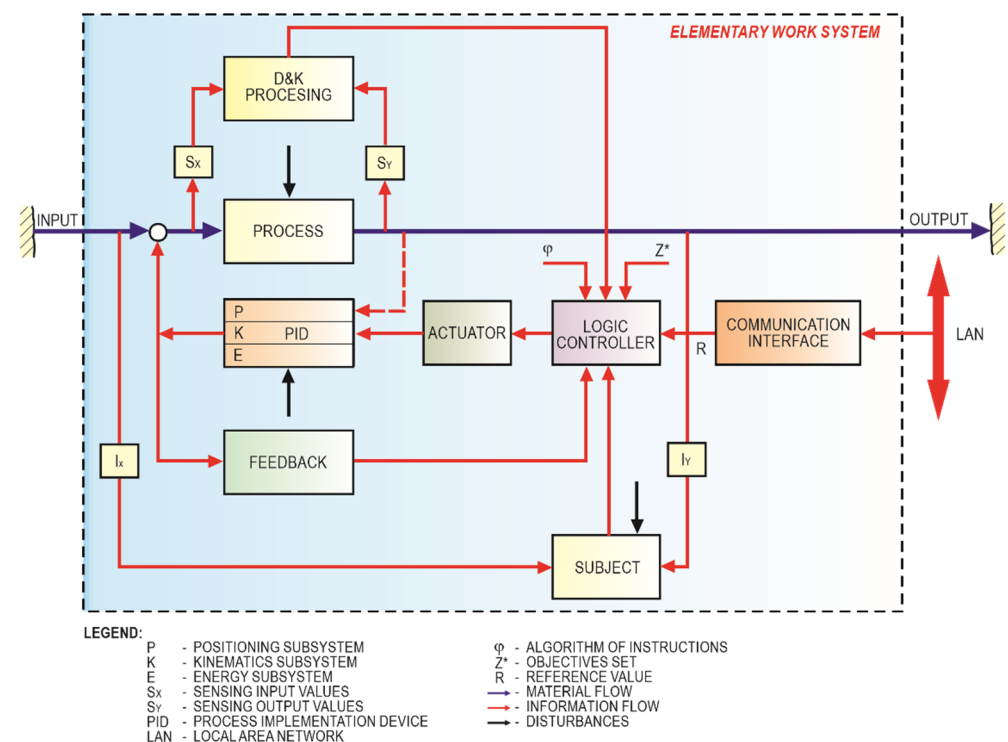


Figure 8. Structure of elementary work systems [32].

2.3. Cyber-Physical Production Systems

Before we define the term “cyber-physical”, we must first define the term “cybernetics”, which comes from the Greek word “kibernein”, meaning to manage. The foundations of cybernetics in its present form were laid in 1948 by the American scientist Norbert Wiener in his book “CYBERNETICS or control and communication in the animal and the machine” [33].

William Gibson, based on the foundations of cyber science, defines the concept of “cyberspace” as new and unknown dimensions [34]. Under the influence of the development of the Internet, the term “cyberspace” is becoming increasingly common and familiar in everyday life. It often becomes synonymous with the digital space that surrounds us and is enabled by advanced technological applications that can share and exchange data, information and knowledge with other participants of the digital space.

Cyber-physical systems (CPS) [35,36] are a new generation of systems that integrate computational and physical capabilities. According to [37], the CPS are systems of collaborating computational units that are intensively connected to the surrounding physical world and its ongoing processes, while providing and using data access and processing services available over the Internet.

In [37] Monostori et al. defined Cyber-Physical Production Systems (CPPS) as a production system that uses CPS-related technology, including devices embedded in different pieces of equipment, to form a concurrent network via continuous computation and communication to enhance the flexibility and adaptability of the industrial production system in the case of a complicated production environment and changing demand, thus improving the personalized and highly efficient nature of modern industrial manufacturing.

CPPSs are a basic building block of the paradigm of smart manufacturing systems (SMS) and enable the concept of Industry 4.0 [3,5,37–42].

In [42], CPPS must be able to analyze data in real time and make decisions autonomously or through hybrid interactive decision processes. Hybrid interactive decision processes between humans and machines use the specific capabilities of humans and CPS in a synergistic way to actively interact with humans and other digital and physical objects.

The model of cyber-physical elementary work systems based on the CPPS concept [3] is shown in Figure 9.

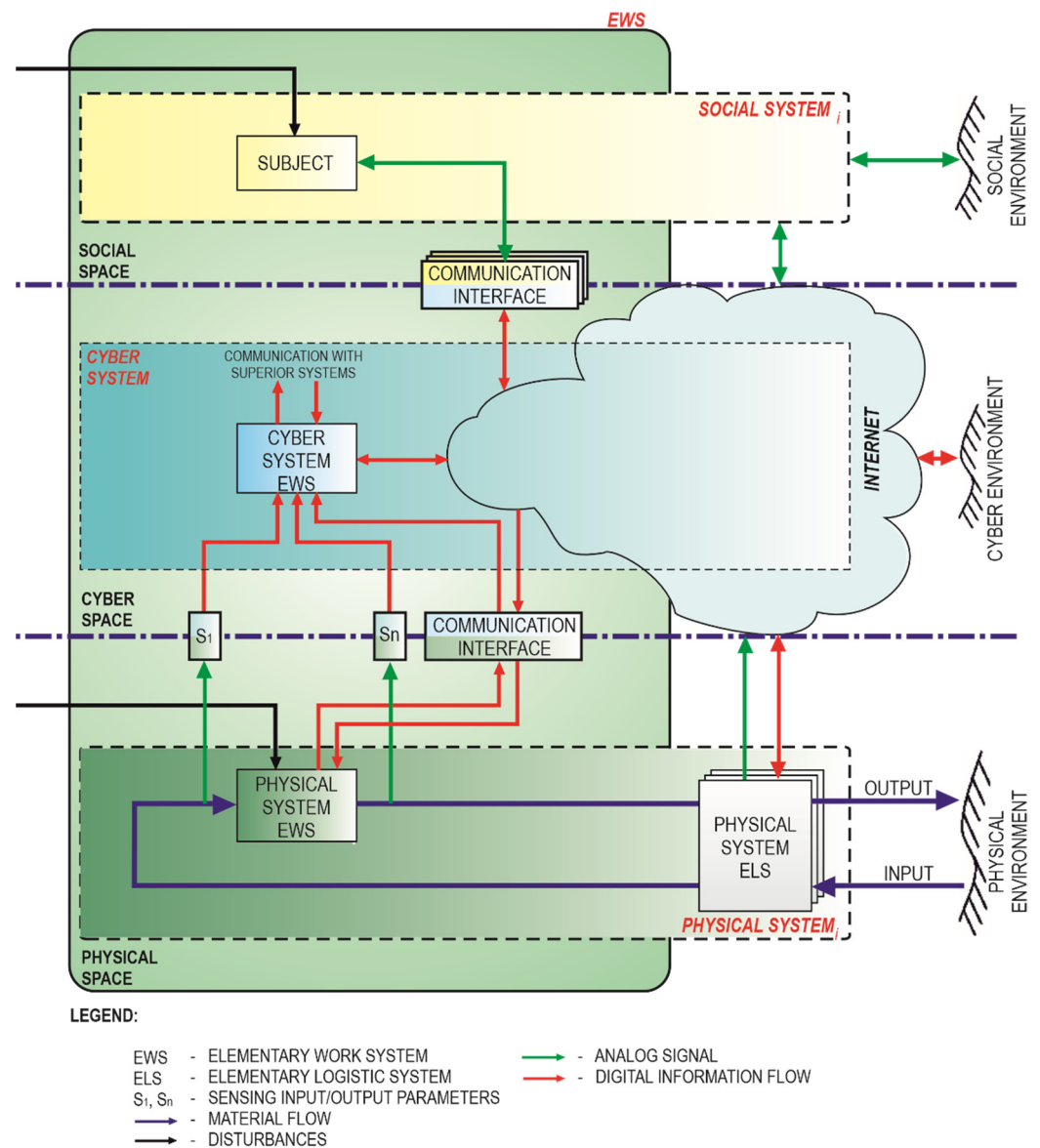


Figure 9. Model of the cyber-physical elementary work system [3].

The conceptual model shown in Figure 9 consists of three subsystems: (1) social system, (2) cyber system, and (3) physical system. Each system exists in its own environment and contains building elements in its own space. The human is the structural element of the social system, the physical system EWS is the structural element of the physical system, and the cyber system EWS is the element of the cyber system in the cyber space. Each element has the corresponding relationships with its specific environment.

The connectivity between individual systems and thus between spaces is enabled by communication interfaces and smart sensors.

The PWS structure is based on the EWS structure [24].

A social system is an organizational unit in which certain specific relationships and rules apply. The human, as the basic building block of the social system, establishes collaborative links with other actors in the social process to implement business processes. The interactions within the social system in today's global world do not only take place within the social space. Advanced ICTs have made it possible to move the mutual interactions between actors into cyberspace.

The new element of the model is the cyber system. The structure of the EWS cyber system is shown in Figure 10.

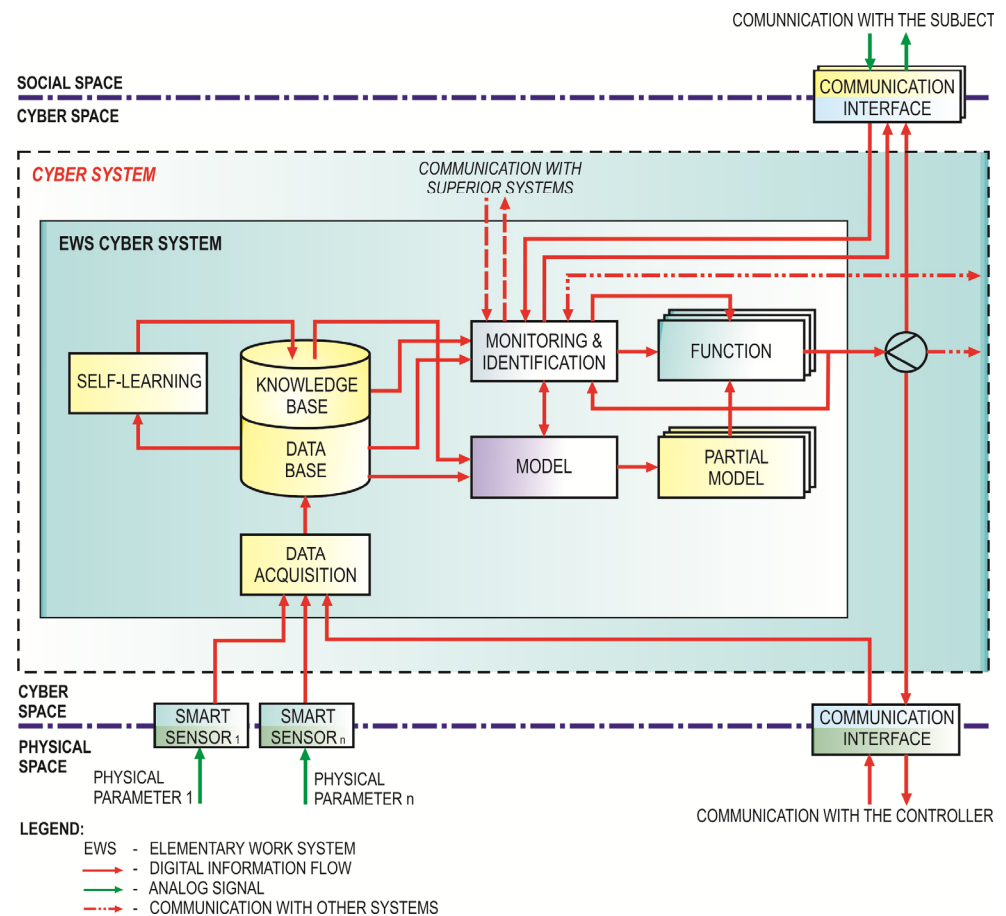


Figure 10. Structure of the EWS cyber system in the CPPS concept [3].

According to [3,25] the basic structure of the EWS cyber system is divided into three basic parts: (1) the data-acquisition part, (2) the self-learning part, and (3) the state-monitoring and identification part.

An important part of the EWS cyber system is the data acquisition, which enables the transfer of data from physical space to cyber space.

The second part of the EWS cyber system is self-learning. This function is based on the database where data is collected in real time from the function of data acquisition.

The third part of the EWS cyber system is the monitoring and identification of the state of the PWS of the EWS. The conceptual model of the CPPS [3] enables the digitalization and cybernation of manufacturing work processes.

Brennen and Kreiss [43] define digitization as the introduction or increased use of digital or computer technology by business, industry, government, etc. Henriette et al. [44] emphasize that digital transformation includes the implementation of digital solutions in the transformation of business models that affect entire organizations, operational (work) processes, resources, and internal and external users. Several authors highlight the features and benefits of the implementation of digitalization in the field of production and its manufacturing systems, such as increased responsiveness, better utilization of resources, an increase in quality and a reduction in the number of complaints due to faulty documentation, an increase in accuracy in meeting delivery deadlines, etc.

The digitization in CPPS can be defined as the transfer of processes to the digital environment and their implementation using digital mechanisms. Functions performed in digitized processes represent digitized functions, as shown in Figure 11a.

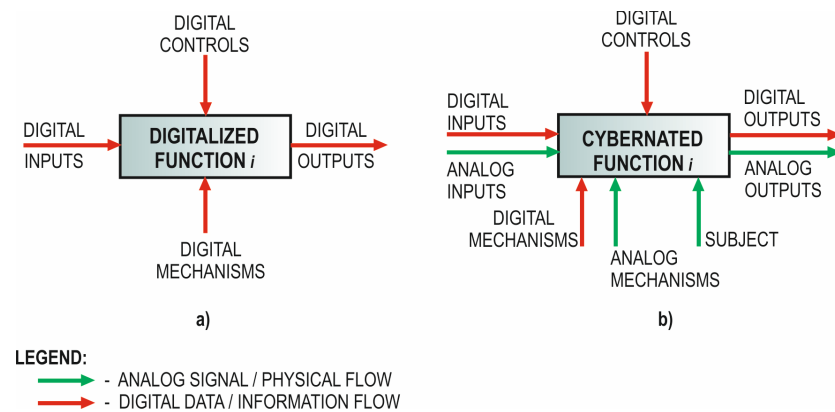


Figure 11. Digitalized and cybernated functions.

Digitized functions are fully automated. Digital mechanisms are embedded in software (classic algorithmic solutions or based on artificial intelligence) that enable the implementation of digitized functions. Digital controls represent a digital form of control mechanisms (with constraints, rules, instructions, etc.) that control the flow of the implementation of digitized functions. Examples of digitization in production can be found in the areas of material ordering, production planning, purchasing in supply chains, accounting, financial transactions, etc.

Digitization thus enables the transformation of many information processes in the production domain as well, and is already taking place intensively, but in production we also have many other processes that cannot be digitized in addition to pure information processes.

These are material-transformation processes that are analog in nature (material processing processes, assembly processes, logistics processes, product-testing processes, etc.). These processes include both analog material flows and the digital processing of data and information in the context of computer-based control and monitoring. The implementation of processes requires both physical elements (such as machines and devices, actuators, sensors, but also people, etc.) and computer elements (logical controls, digital processors, control programs, databases, etc.).

Thus, today's production systems consist of many physical and digital elements interconnected in a "hybrid" analog-digital world, with the digital component becoming increasingly important and advanced, enabling the realization of advanced control and monitoring functions in the context of the interconnection of social, digital and physical space, see Figure 9. This opens the way to cybernation.

Cybernation in manufacturing systems is the advanced computerized monitoring, control and management of the physical elements of the manufacturing system, which include processes, machines, process implementation devices (PIDs) and humans using digital computer elements, such as logic controllers, digital processors, control programs, databases, etc.

Functions performed in cybernated processes represent cybernated functions, as shown in Figure 11b. Cybernated functions are performed in a hybrid analog and digital world. Their inputs and outputs are analog and digital in nature.

Digital mechanisms (artificial intelligence, cognitive technologies, etc.) and physical, analogue mechanisms (PIDs, actuators, sensors, humans, etc.) provide for the implementation of cybernated functions. The artificial intelligence and cognitive technologies as digital mechanisms are presented in the next section.

Digital controls, similar to the implementation of digitized functions, represent digital control mechanisms in the form of rules, instructions, etc.

Cybernated functions can refer to a process (e.g., performance monitoring of a process, self-organization of work processes, etc.), to a PID (e.g., monitoring the state of a tool and taking action based on that monitoring) or to the human (e.g., monitoring commands by the human, informing the human, etc.).

The digitalization and cybernation of the work process in the field of manufacturing systems have fundamentally changed the role of the human in the manufacturing system.

2.4. Artificial Intelligence and Cognitive Technologies

Although artificial intelligence (AI) and cognitive technologies are not the same, the terms are often used interchangeably because both technologies aim to mimic human intelligence. The difference is that cognitive technologies focus on specific areas of human cognition, such as language and vision, while AI covers a broader range of technologies and applications. The easiest way to explain the difference between the two technologies is to say that cognitive technologies are a subset of AI technologies.

But before that, we need to look at the definitions of intelligence, which are essential for understanding what machines or computers are supposed to replace. There are many definitions. Pfeifer and Scheier [45] summarized from the Journal of Educational Psychology the writings of 14 leading experts of the time, who gave 14 different answers as to the definition of intelligence. To cite just a few summaries of the answers: “the ability to think abstractly (L. M. Terman); to learn or the ability to learn to adapt to one’s environment (S. S. Colvin); the ability to adapt oneself appropriately to relatively novel situations in life (R. Pintner); the biological mechanism by which the complexity of the effects of stimuli combine to give somewhat unified behavior (J. Peterson).”

Almost 100 years later, the definitions of intelligence are not significantly different, and there are still as many definitions as there are experts in the field. Legg [46] has collected as many as 71 definitions of intelligence, which he divided into the following areas: collective definitions, psychologist definitions and AI researcher definitions. One of the more comprehensive definitions is given by Sternberg [47], who states that intelligence is “mental activity directed toward purposive adaptation to, selection and shaping of, re-al-world environments relevant to one’s life”. He developed the Triarchic Theory of Intelligence or Three Forms of Intelligence, which argues that three types of mental processes are necessary for intelligent behavior. These are analytical intelligence, which compares, evaluates and analyses, creative intelligence, which generates insights, inventions and other creative endeavors, and practical intelligence for applying what people have learned in everyday life.

The term artificial intelligence was coined in 1956 at a conference at Dartmouth College in New Hampshire (USA) organized by John McCarthy (Stanford) and his friend Marvin Minsky (MIT). The goal of the conference was to bring together researchers from different fields to create a new area of research dedicated to the development of machines that could simulate human intelligence [48].

Just as there are many definitions of intelligence, there are many definitions of AI. A short and meaningful definition is given by Poole and Macworth [49], who say that artificial intelligence is real intelligence created artificially. Guid and Strnad [50] refer to AI as a universal intelligent system or an artificial human. In the case of the item, the input and output are connected by an internal representation (Figure 12). From Figure 12 we can see that AI is connected by computer vision and natural language (hearing). Within the intelligent system, we have learned knowledge, reasoning, planning, interpretation, and machine learning. At the output we have actuators (robotics) and speech.

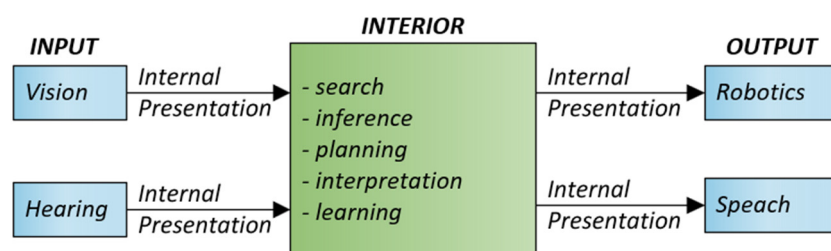


Figure 12. Universal Intelligent System or Artificial Human [50].

AI technologies include:

- **Machine learning:** Machine learning uses algorithms that can learn from data and improve their performance without being explicitly programmed [51]. There are different types of machine-learning algorithms. In supervised learning, AI systems learn from a set of data for which we also know the output (the outcome). The goal of supervised learning is to compute the parameters of functions that convert the input data into output data. The system is well learned if the error between the computed output and the actual output is minimal or ideally zero. In unsupervised learning, we do not know the output data, only the input data. The system itself looks for patterns and correlations in the data. This type of machine learning usually solves clustering and dimensionality-reduction tasks. In reinforcement learning, we provide feedback to the system in the form of rewards or punishments. The goal is to learn a strategy that maximizes cumulative rewards. Examples of applications include games such as chess and Go. In deep-learning technology, we use neural networks that consist of input, hidden, and output layers. At the core of neural networks are artificial neurons located in nodes that simulate human neurons. For each neuron, the learning phase calculates as many parameters as it has synapses (connections) to other neurons, as well as a threshold parameter (eigenvalue) of that neuron. The data on the output grid is obtained from equations with a large number of parameters set by the neural network during the learning process. In today's chatbots or large language models (LLM), many parameters are computed that are set during the learning phase. The LLM ChatGPT has 175 billion parameters, and the LLM LaMDA has as many as 500 billion parameters [52]. Deep neural network technology is used for tasks such as image classification, natural language recognition and processing.
- **Natural Language Processing (NLP)** deals with the interaction between humans and computers in natural language. It includes techniques such as text classification, sentiment analysis, translation between languages, question answering, text summarization, text generation and text recognition [53].
- **Robotics** deals with the design, construction, and use of robots. Narrowly speaking [54]: "A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions to perform a variety of tasks."
- **Computer vision** is also a branch of AI that deals with the ability of computers to interpret and understand visual information, such as images and videos. It involves techniques such as object recognition, image segmentation, and image captioning [55].
- **Expert Systems** mimic the human expert in a particular field. They use a knowledge base, an inference engine, and a user interface to perform tasks such as diagnosing problems and providing recommendations. They have not achieved widespread success because it is difficult to encode human knowledge into rules. We are talking about an expert-systems bottleneck.
- **Evolutionary Computing:** Evolutionary computing is also a branch of AI. Includes the use of natural selection and genetic algorithms to optimize solutions to problems. It is inspired by the process of biological evolution. The selection of the best solutions based on some criteria, and recombination of the best solutions to generate new solutions are crucial [56].

Goodfellow et al. [51] reviewed the literature compiled and summarized the findings that the second wave of neural network research in the 1980s brought with it a wave of connectionism or parallel distributed processing that emerged in the context of cognitive science. They also noted that cognitive science is an interdisciplinary approach to understanding the mind that combines several different levels of analysis.

Cognitive technologies include:

- **Natural Language Processing.** NLP is used in a variety of applications, including chatbots, machine translation, and emotion analysis.

- **Computer Vision.** Computer vision is used in a variety of applications, including facial recognition, object recognition, and autonomous vehicles.
- **Decision-making technologies** to support human decision-making processes by using techniques such as machine learning and natural language processing to analyze data and make recommendations or decisions. Decision-making technologies are used in a variety of applications, such as marketing, finance, and healthcare. However, these are not the only areas. Olan et al. [57] showed that these technologies can be used to analyze consumer data to understand behaviors and preferences, and make recommendations to companies about the best products to offer to specific consumer segments.
- **Forecasting.** We use machine-learning algorithms to build forecasting models that predict future events or trends. Kelleher et al. [58] presented a range of algorithms and techniques for prediction, including supervised learning, unsupervised learning, and reinforcement learning, using examples and case studies.

In summary, cognitive AI technologies refer to AI systems designed to process, analyze, and make decisions based on data, much like the human brain. NLP, Computer Vision are fields of AI technologies. There are also decision-making technologies and forecasting, which are implemented through machine learning.

From the above, we can summarize that a cognitive process is the acquisition and development of cognitive abilities and skills, especially in the context of artificial intelligence and machine learning. Therefore, this technology becomes very important as it enables machines to perform tasks that were previously reserved for humans.

Just as AI technologies and cognitive technologies are similar, so are intelligent agents and cognitive agents. They also have their own characteristics that distinguish them.

Guid and Strnad [50] explained that an intelligent agent is a device or program that uses sensors to receive data from the environment and actuators to act on the environment. Finally, the word agent is derived from the Latin word “*agere*”, which means to act. The behavior of an agent is described by an agent function that converts a sequence of sensations into an action. In computer science, an intelligent agent is a software agent that adapts and learns, thereby exhibiting some form of intelligence. In this context, an agent program is an implementation of an agent algorithm.

There are several types of agent programs. Guid and Strnad [50] divide them into: simple reflex agents, model-based reflex agents, goal-based agents, utility-based agents, and learning agents. The most sophisticated are the learning agents. A typical example is a lightly automated cab that satisfies the following performance criteria: safety, speed, comfortable driving according to regulations, and profit optimization. Other examples are e.g., a chatbot for customer service and an image-recognition system

Cognitive agents are a subset of AI agents. These are agents that mimic human-like intelligence. In order to do this they are equipped with advanced natural language processing capabilities and are able to understand, reason, and learn from large amounts of data and the tasks they perform. Cognitive agents are able to interact with humans in a more natural and intuitive way. Another difference is the degree of autonomy. Because cognitive agents have more autonomy, being able to learn from their environment and adjust their behavior accordingly, they are more adaptable and flexible, which is critical for complex decision-making tasks. The third and perhaps most important difference is that cognitive agents can learn from experience. As a result, they can be more effective in complex decision-making tasks.

Agent technology allows the implementation of distributed, highly adaptive manufacturing systems. The papers [59–64] contain a more comprehensive description of agents and multi-agent systems and their use in the field of manufacturing systems.

In the next section, the change of the role of humans in manufacturing systems through industrial revolutions is presented.

3. The Transformation of the Role of the Human in Manufacturing Systems through the Industrial Revolutions

The evolution of the human's role in manufacturing systems is illustrated in Figure 13, which shows the functional levels at which the human's role in the manufacturing system was established over time.

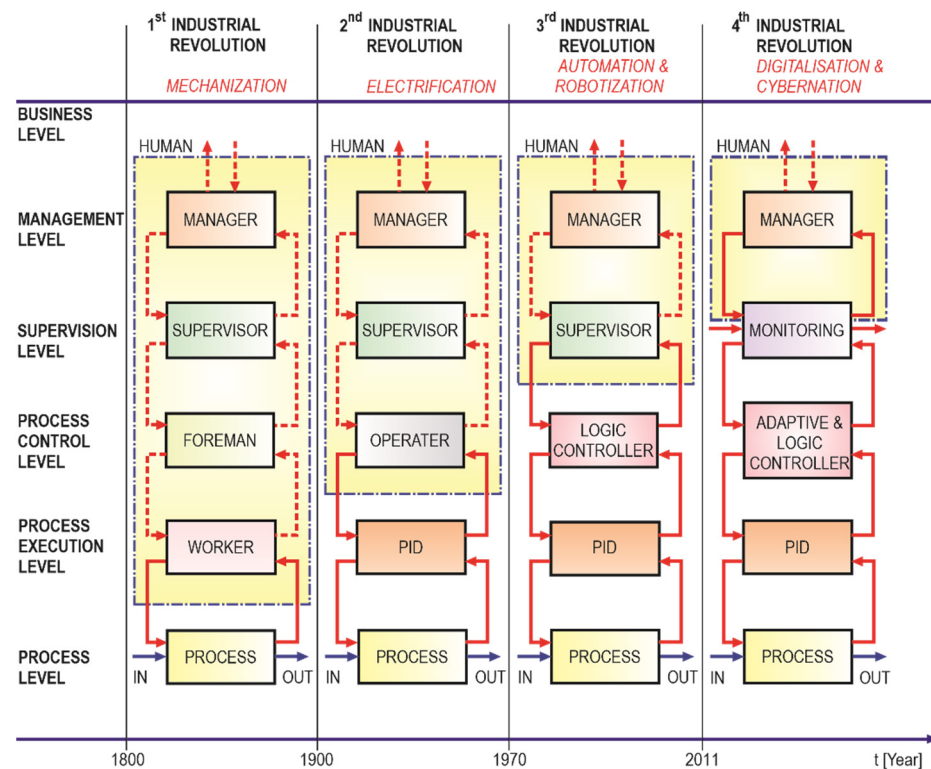


Figure 13. Evolution of the human's role in manufacturing systems over time [65].

In the early days of industrial production the role of the human was closely related to the process itself, i.e., at the level of implementation.

The human was the one who carried out the process, controlled it and at the same time exercised control over it. The human was the source of power. Such a role of the human required hard physical work and at the same time limited his/her creativity.

The concept of workforce, which denotes the fundamental role of the human in the manufacturing system, also originates from this period. Thanks to technological progress in the mechanization of work, the implementation of the process was taken over by machines and devices, and the human moved away from the actual implementation of the process to the level of operation or device control.

Industry 2.0 also radically changed manufacturing. The system of work and operations management in manufacturing is based on the principles of scientific management founded by F.W. Taylor. The human was relieved of heavy physical work as machines took over. However, the human's activity was limited to the implementation of a single, well-defined and standardized operation. This led to a large increase in efficiency and productivity under the conditions of mass production, while at the same time creativity and the use of human intellectual potential were reduced to a minimum. The term workforce has been preserved.

The development of NC technology and the flexible automation of work devices based on computer controlled to Industry 3.0. The function of controlling machines and devices was taken over by NC, CNC and PLC controllers. Computer control introduced the flexibility of production, because when the control program is changed, the process also changes. Thus, the human has moved away from the direct process and can focus

on the management and control of manufacturing systems, for which solutions have already been developed to provide computer support for these activities (e.g., planning and scheduling systems, CAD/CAM systems, computer databases, etc.), further increasing the flexibility of manufacturing and ensuring efficiency despite a reduction in batch sizes. The term workforce to describe human resources has lost its meaning in the context of flexible manufacturing.

The role of the human has changed significantly from the beginning of industrial production to the present day. As can be seen in Figure 6, during the first three industrial revolutions, the human evolved from the level of process execution to the level of supervision. The hard work is being done by the technology, or the rather physical elements: mechanical devices, sensors, actuators, computer controllers, monitoring and data-acquisition systems, etc.

In the context of Industry 4.0, most routine processes are automated as a result of the intensive digitization and cybernation of work. Thus, the human mainly carries out creative, knowledge-based development processes as well as management and decision-making processes, which can, however, be intensively technologically supported in real time and from anywhere. The term workforce loses its meaning completely in this context.

What can we expect from the next step? How can the introduction of advanced cognitive technologies and AI into the CPPS contribute to the development of the role of humans in manufacturing? We will try to find answers to these questions in the rest of this paper.

3.1. Towards Industry 5.0

The term Industry 5.0 has started to appear in scientific publications [66–70] in the past five years. The first authors to use the term Industry 5.0 were Özdemir and Hekim [66]; they described how human agency and technology can be reconciled in an increasingly connected world. According to [71], Nahavandi [67] proposes another demand for Industry 5.0, emphasizing the need to find a solution that allows manufacturers to increase productivity without removing human workers from the manufacturing.

Different industry practitioners and researchers have provided various definitions of Industry 5.0. In [72], Industry 5.0 is seen as the next industrial evolution.

“Industry 5.0 brings the human workforce back to the factory, where humans and machines are paired to increase process efficiency by utilizing human intelligence and creativity through the integration of workflows with intelligent systems” [67].

According to [73], Industry 5.0 is a necessary advance from Industry 4.0 and offers a different focus and underlines the importance of research and innovation to support industry in its long-term service to humanity within the planetary boundaries. The concept of *Industry 5.0* was defined by the European Commission as follows [73]:

“Industry 5.0 recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries for our planet and placing the wellbeing of the industrial worker at the centre of the production process”.

Based on a literature review, resilience, sustainability and human-centricity represent key concepts at the heart of the new industrial revolution, the so-called Industry 5.0 [73–75]. According to [71], resilience refers to the attitude of manufacturing systems and organisation to overcome economic crises and maintain competitive advantages over competitors; sustainable refers to manufacturing systems that promote energy-efficient, cleaner manufacturing and circular economy practices; the human-centricity refers to the development of the new manufacturing systems that involve workers. In [76] the authors present the use of product-design strategies to implement the circular economy.

The new idea of Industry 5.0 appeared as an extension of Industry 4.0 with social and ecological dimensions [74]. In [77] the authors emphasize that Industry 5.0 is envisioned as a coexisting industrial revolution [78] for which two visions have emerged: (1) human-robot

collaboration and (2) a bioeconomy in which renewable energies are used as biologically resources to transform existing industries [79].

The concept of Industry 4.0 is more technology-oriented, while Industry 5.0 is more value-oriented towards practical implementations of available enabling technologies in industry [80]. The development from Industry 4.0 to Industry 5.0 is shown in Figure 14.

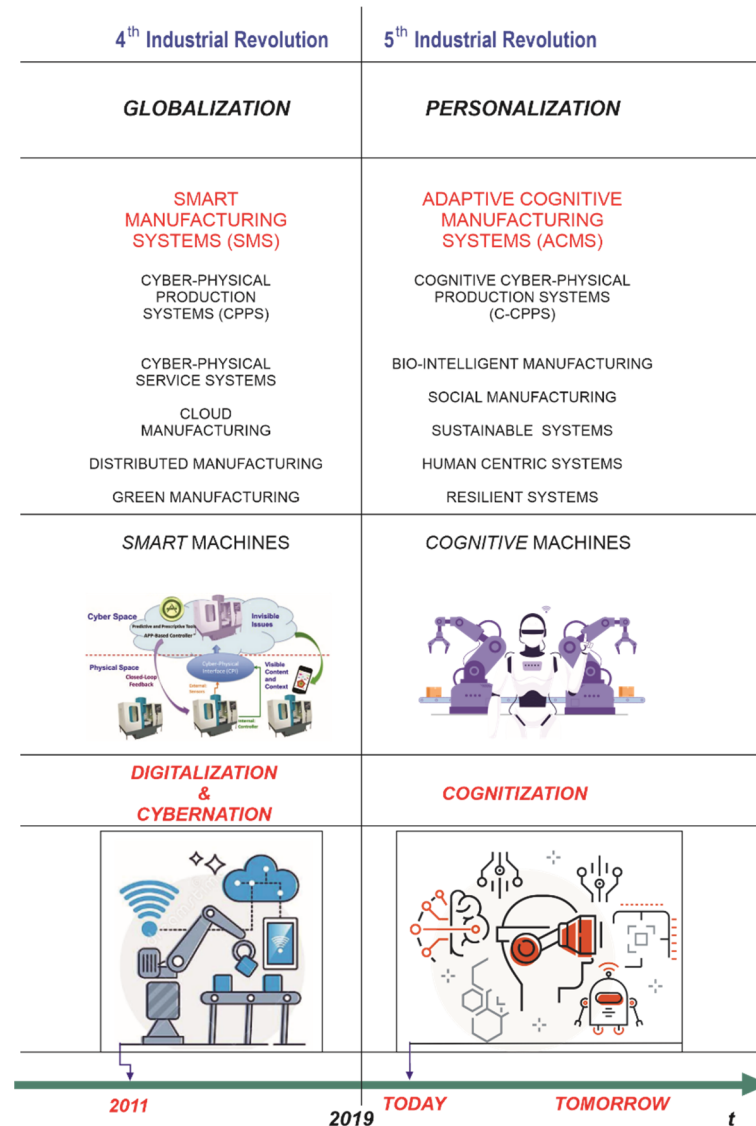


Figure 14. Evolution from Industry 4.0 to Industry 5.0.

The industrial production of the 21st century, under the constant pressure of globalization, is characterized by regionalization, widespread presence and the increasing personalization of products, with each customer looking for a product according to his/her own wishes, which significantly increases the variants of each product and their diversity with regard to the required production quantities.

In [81] the authors identified the framework of the concept of Industry 5.0. The framework of the Industry 5.0 concept is based on the symbiosis of the three segments: technology, social affairs and ecology form the essence of Industry 5.0 [81]. Also in [81] the authors presented a collection of scientific studies emphasizing the need for human symbiosis with new technologies. The human symbiosis with technology was presented in [82]. Similarly, Bernar and Welh described “*Smart Working*” practices in [83].

In [19,84] ElMaraghy et al., have a vision for the new paradigm of future adaptive cognitive manufacturing systems (ACMS), and the characteristics, drivers and enablers are presented.

According to ElMaraghy et al., these systems “*will feature maximum flexibility, physical and logical scalability, and agility; and utilize more static, dynamic, and cognitive adaptability enablers to improve productivity and emphasize all three facets of sustainability; increase shared human-machine collaboration and decision making, replace implicit interactions with explicit tasks sharing, and enjoy greater visibility throughout*” [19].

Based on the European Commission document [74] the authors in [78] identified the following key technologies for the transition from Industry 4.0 to the concept of Industry 5.0: (1) individualized human-machine interaction technologies that connect and combine the strengths of humans and machines, (2) bio-inspired technologies and smart materials that enable materials with embedded sensors and enhanced features, while being recyclable, (3) digital twins and simulations to model entire systems, (4) data transmission, storage and analytics technologies, capable of handling data and system interoperability, (5) artificial intelligence, for example, to detect causalities in complex, dynamic systems, leading to actionable intelligence, (6) technologies for energy efficiency, renewable energy, storage and autonomy.

The key enablers of Industry 5.0 are CPPS, artificial intelligence and cognitive technologies. The implementation of the cognitive technologies and artificial intelligence in the CPPS paves the way for a new generation of advanced manufacturing systems, the so-called Cognitive Cyber-Physical Production Systems (C-CPPS).

3.2. Cognitive Cyber-Physical Production Systems—A New Concept

The cognitive cyber-physical production systems (C-CPPS) are basic building blocks of the paradigm of adaptive cognitive manufacturing systems (ACMS) and enable the concept of a 5th industrial revolution.

The C-CPPS are based on the implementation of advanced cognitive technologies and AI as the digital mechanisms for the realization of digitalized and cybernated functions (see Figure 5) in the CPPS cyber system.

Structure of a Cognitive Cyber-Physical Production System

The concept of cognitive cyber-physical production systems (C-CPPS) originates from the work of Hozdić et al. [3], where a cyber-physical EWS is introduced and defined as a basic building block of CPPS (see Section 2.3).

The C-CPPS concept introduces the cognitive technologies and AI in the cyber system of CPPS.

The basis for the construction of the model of the C-CPPS cyber system is the concept of the three-level architecture of the multi-agent model for the distributed control of manufacturing systems described in [85]. The C-CPPS model is shown in Figure 15.

Tangible elements such as physical work systems are present in physical space. The control of these physical elements is carried out via adaptive logic controllers (ALCs).

Tangible elements are thus represented in cyberspace by agents. The connection between the physical and the cyber space is enabled by communication interfaces. The connection of the multi-agent system (MAS) to a standard functional block CLIENT/SERVER for bi-directional data transfer based on the TCP/IP communication protocol enables real-time bi-directional communication between the operational level functions of the cyber system and the executive functions of the physical system.

In the social space we have the human that communicates with cyberspace through a communication interface. The user services are located in such a communication interface, which is different from the communication interface between cyberspace and physical space. The fundamental role of the communication interface between social and cyber space is to receive the human's goals/commands and to display to the human the intelligible results that result from the program operations in cyberspace.

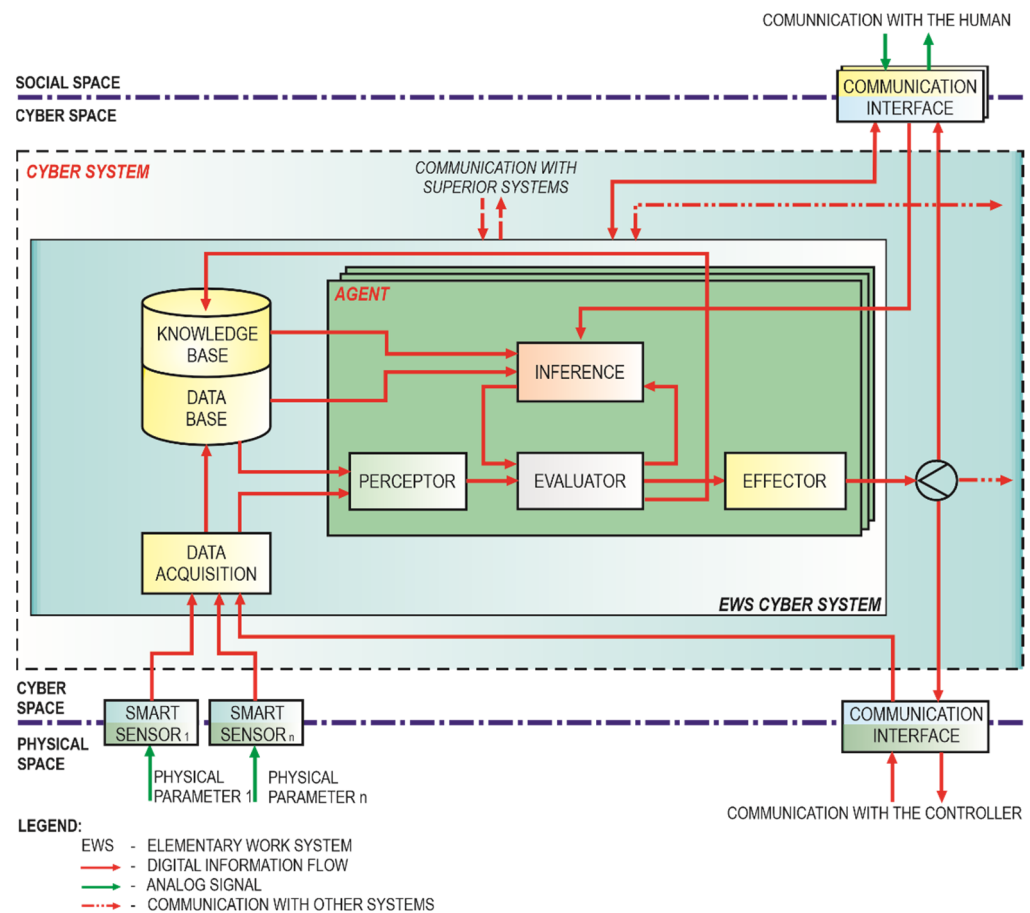


Figure 16. EWS cyber systems of the CPPS in the C-CPPS concept.

According to [89], the agent is associated in [88] with the identification code ID , the agent structure Ω_{Agent} , the objective function $Role$, the actions Act , the interactions $Interact$, the behavior $Behaviour$, the language $Ling$, and the agent type $Type_{Agent}$ defined.

The agent identification code ID_{Agent} is the identifier of an agent in a MAS. Different agents have different identification codes.

According to [89], the structure of the agent Ω_{Agent} is defined by four structural elements: perceptor $Perception$, effector $Effector$, inference controls $Mech_{Agent}$, and evaluator $Evaluator$.

The function $Role$ represents the function that each agent performs.

The set of actions that a single agent can perform to realize certain functions are written in Act . The communication between the agent and its environment is also described in Act . Communication between agents defines interaction $Interact$.

The behavioral mechanism $Behaviour$ of the individual agent provides for the simultaneous execution of activities within the agent itself, allowing the agent to perform several different functions simultaneously.

$Ling$ is an agent-communication language. For proper communication between agents, a suitable ontology must be defined that allows agents to understand each other and connect with agents of other multi-agent platforms (MAPs).

Agent type $Type_{Agent}$ generally defines three types of agents: (1) agents representing physical elements in a cyber system of C-CPPS, (2) agents representing digital (cyber) elements in a cyber system of C-CPPS, and (3) agents representing humans in a cyber system of C-CPPS.

The introduction of cognitive technologies and AI in CPPS will strongly influence the role of the human in manufacturing systems. The following is a vision of the transformation of the human's role in the transition from Industry 4.0 to Industry 5.0.

3.3. The Transformation of the Human's Role in Manufacturing Systems towards Industry 5.0

The role of the human will change in the next generation of production systems. Digitalization and cybernation are already making direct human labor activity completely redundant in some processes, so the question arises: What role will the human play in the production systems of the future? Here we have to start from the fact that only the human has the motive and the benefit from operating production systems.

The development of new CPS concepts in the field of production therefore represents an important step in the evolution of organizational and systemic forms of production structures and their transition from social-technical to cognitive social-cyber-physical systems.

Restructured CPPS become systems with some degree of cognition, or they become so-called “cognitive systems”, which allow much greater agility and adaptability of the elements of production enterprises to the needs of the modern market and society.

In the proposed C-CPPS concept, the role of the human (by which we mean individuals, groups, and/or the whole collective) changes. This significantly alters the principles of structuring sociotechnical systems from the perspective of modern achievements.

The role of the human is formed in two directions: (1) in the direction of generating new ideas and innovations with the intensive use of explicit knowledge, social technologies, creativity and intuition (the human as a knowledge co-worker) and (2) in the direction of C-CPPS management in real time based on on-line information, diagnostics, prognostics and decision models (the human as a decision maker), see Figure 17.

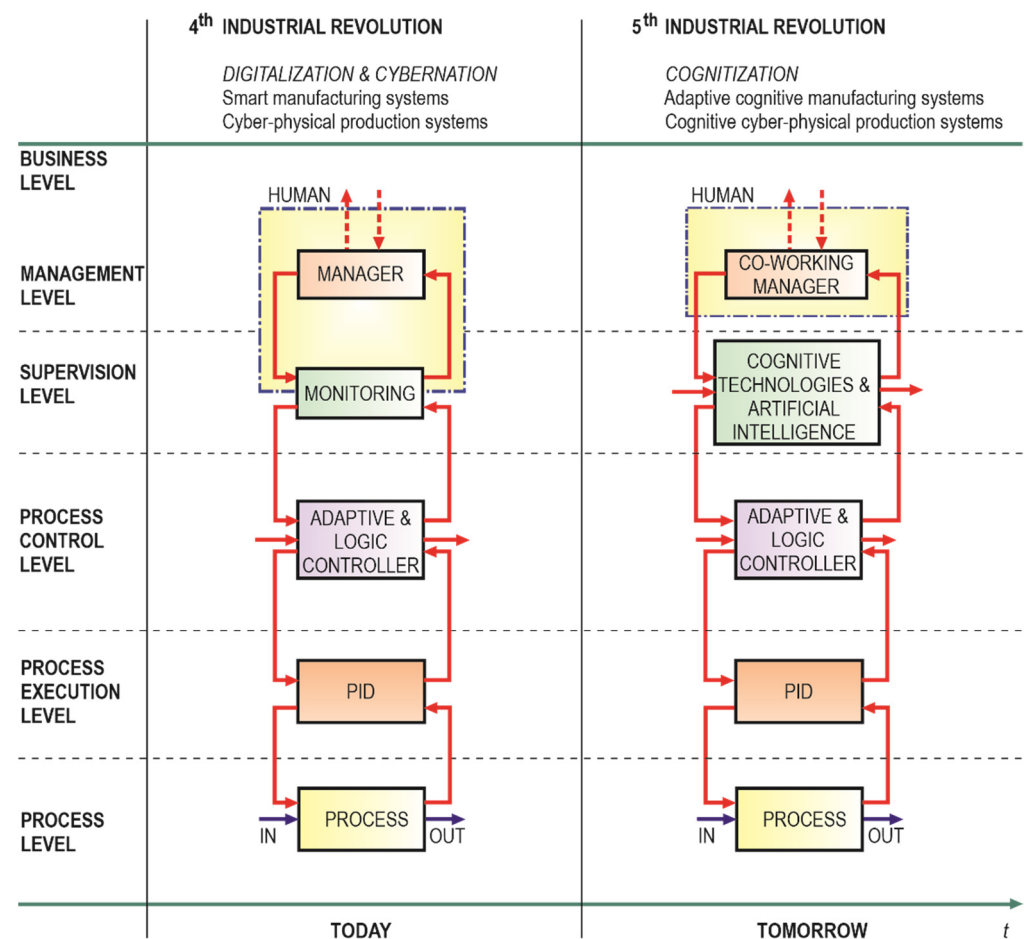


Figure 17. Transition of the human's role from Industry 4.0 to Industry 5.0.

As indicated in Figure 17, we can assume that the human only has a function at the highest level, i.e., the management level. At this level, the human will be equipped with digitalized and cybernated functions (such as: self-learning function, prediction function,

self-diagnosis function, self-organization, etc.) and support systems (cognitive technologies and artificial intelligence) that will enable him/her to manage the system in real time and from any place. This will allow him/her a high level of real-time decision-making and communication, cooperation and coordination (co-working) with other elements of the manufacturing system.

The management of modern production systems is a very challenging task due to their increasing complexity. This affects all actors in the production systems as well as the performance of the production systems themselves. For this reason, the application of the concept of digitalization and cybernation of functions in the C-CPPS and the use of artificial intelligence and cognitive technology in real production systems brings significant improvements. The implementation of digitalized and cybernated functions in C-CPPS, such as planning, scheduling, and self-organizations, will make it possible to solve the problem of production planning and control. In this case, the role of humans will be taken over by AI and cognitive technologies.

In future advanced manufacturing systems such as C-CPPS, the human factor will continue to play a very important role in interactive decision-making at the operational, collaboration and coordination, and business levels.

4. Conclusions

The article describes in detail the historical development of production systems with an emphasis on the evolution of the role of human in the manufacturing system through the evolution of industrial revolutions.

In the review of the scientific literature on the subject of the article, the development of the manufacturing system from the earliest beginnings of industrial production to modern smart production systems (SMS) of Industry 4.0 and their basic building blocks of the so-called cyber-physical production systems (CPPS) is systematically presented.

The implementation of CPPS concepts and the development of AI and cognitive technologies have paved the way for a new industrial revolution, the so-called Industry 5.0. Key concepts at the heart of the new industrial revolution, such as resilience, sustainability, and human-centricity, have steered the evolution of production systems into the paradigm of adaptive cognitive manufacturing systems (ACMS) and their basic building blocks of so-called cognitive cyber-physical production systems (C-CPPS).

The advantages and disadvantages of the new industrial revolution and its manufacturing systems compared to the fourth industrial revolution can be viewed from different angles such as: objectives, systemic approaches, human factors, enabling technologies and concepts, and environmental impacts [90].

The study is based on comparing the role of the human in production systems through industrial revolutions, not comparing and identifying advantages and disadvantages between Industry 4.0 and Industry 5.0.

The introduction of the key technologies of the industrial revolutions, such as mechanization, electrification, automation and robotics, digitalization, cybernation and cognition, had a radical impact on the change of the human's role in the manufacturing system and it has been a very important part of the development of the manufacturing system. In this article, the development of the manufacturing system in terms of Industry 5.0 is discussed through the prism of the development of the human role. The human factor will continue to play a very important role in interactive decision making at the operational, collaborative and coordination level of manufacturing system by generating new ideas and innovations with intensive use of explicit knowledge—the human will act as collaborator (a knowledge co-worker).

In the paper, the development of manufacturing systems was discussed from two aspects: (1) the historical aspect and (2) the aspect of the role of human beings in manufacturing systems.

The historical development of manufacturing systems was described in terms of the change from data to cognition in manufacturing systems against the background of the

development of industrial revolutions. Through the industrial revolutions, manufacturing systems have evolved from traditional manufacturing systems and dedicated manufacturing lines to adaptive cognitive manufacturing systems. In this paper we structured a new conceptual model of manufacturing systems based on the development of the CPPS concept. As one of the approaches to adaptive cognitive manufacturing systems of the future, the concept of C-CPPS was introduced and defined.

The C-CPPS use cognitive technologies and AI to be more resilient, responsive, adaptive, sustainable, and human-centered. Future C-CPPS will: (1) be maximally digitized, cybernetized, networked, flexible, and agile; (2) be strongly supported by the new cognitive technologies of Industry 5.0; and (3) enable increased collaboration between humans and machines, and focus on all aspects of sustainable development.

In structuring the new concept of C-CPPS, physical, cyber and social systems are aggregated to achieve common goals and create a space that takes on the characteristics of a cognitive environment. Aggregation has different implications. On the one hand, we can expect positive effects that lead to the achievement of positive, desired results, but on the other hand, such a grouping can also have negative effects because the grouping itself cannot be controlled. Such integrative processes undoubtedly increase the complexity of manufacturing systems, which requires a more explicit analysis of integrative factors. In the future, the basic principle of production must be based on the premise that production must serve man and not vice versa.

Future Research

This study provides a starting point for developing a socio-technical perspective of the fifth industrial revolution. Further research will aim to implement the presented the C-CPPS concept in a real industrial environment.

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