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Human-Centered Intelligent Manufacturing: Overview and Perspectives

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Abstract: Humans are the most dynamic factor in a manufacturing system. Regardless of the advancement level of intelligent manufacturing, it should meet humans' needs and serve for a better life. Based on the theory of human–cyber–physical systems in the context of intelligent manufacturing, the concept of human-centered intelligent manufacturing (HCIM) is proposed in this study. HCIM is discussed from the aspects of background, connotation, human factors, technical systems, and practical applications. This clarifies that HCIM not only reflects an important perspective, but also represents one of the significant research directions of intelligent manufacturing. On this basis, several suggestions are recommended, from policy decision-making, enterprise development, and scientific research levels, including linking HCIM with relevant national strategies, regarding HCIM as a key concept for enterprises' development, and enhancing research on human factors/ergonomics in intelligent manufacturing systems. This study could provide a reference to promote the HCIM development and applications in China.
Keywords: human-centered; new-generation intelligent/smart manufacturing; human–cyber–physical system; human-centered intelligent manufacturing

1 Introduction

The world experiences changes unseen over the past century. In particular, the deep integration of the new generation of information and manufacturing technologies profoundly reshapes the development pattern of the global manufacturing industry. In the face of the new round of scientific and technological revolution and industrial revolution with intelligent manufacturing technologies at the core, countries and regions worldwide employ active actions [1,2] to promote the transformation and upgrading of the manufacturing industry, to secure a favorable position for their manufacturing industry in the industrial development in the future (Table 1). In this process, intelligent manufacturing has become a major option for them to build competitive edges in the manufacturing industry. The academic and industrial communities in various countries have also carried out relevant studies to provide a theoretical basis to promote strategic plans related to intelligent manufacturing [1–5].

In recent years, China has accelerated the pace of intelligent manufacturing development. *China Manufacturing 2025* has proposed a clear goal of completing the historical transition of China from a large to a strong manufacturing industry, by accelerating the deep integration of new-generation information technologies and manufacturing

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industry as the main theme and advancing intelligent manufacturing as the main direction, in accordance with the principles of "innovation-driven, quality first, green development, optimized structure, and talent-based development" [1]. In 2017, the State Council issued *Development Plan for the New Generation of Artificial Intelligence*, detailing the new features of artificial intelligence (AI) and defining intelligent manufacturing as an important direction for the applications of the new-generation AI. Simultaneously, the China's academic community have proposed the human–cyber–physical system (HCPS)-based theory on intelligent manufacturing development, analyzed the paradigm evolution of intelligent manufacturing, and proposed the development strategy and technology roadmap of intelligent manufacturing in China for the coming 20 years [1–3].

Table 1. Industry/manufacturing strategic plans issued by countries/regions.

Year	Country/region	Name
2008	EU	Factories of the Future
2011	US	Advanced Manufacturing Partnership
2012	US	Industrial Internet: Pushing the Boundaries of Minds and Machines
2013	Germany	Industrie 4.0
2013	UK	The Future of Manufacturing: A New Era of Opportunity and Challenge for the UK
2014	ROK	Manufacturing Industry Innovation 3.0 Strategy
2015	China	China Manufacturing 2025
2015	France	Industry of the Future
2016	Japan	Society 5.0
2018	US	Strategy for American Leadership in Advanced Manufacturing
2019	Germany	National Industrial Strategy 2030

Based on the HCPS theory in the context of intelligent manufacturing, human-centered intelligent manufacturing (HCIM) attracts increasing attention among the academic and industrial communities. It is expected to become a key direction in the intelligent manufacturing development. On this basis, in this study, the development background of HCIM was analyzed, its contents are detailed, and its technical system with examples of practical applications is described. Finally, several recommendations for the future HCIM development are proposed.

2 Development background of HCIM

Manufacturing is a process in which humans use tools to transform raw materials into products and services that can meet people's needs in production and life. Intelligent manufacturing is a means to improve the efficiency and quality of such transformation. In manufacturing and production activities, humans are always the most dynamic and energetic factor.

(1) Humans are the ultimate target of intelligent manufacturing services. With the help of new production technologies and changes in production methods, intelligent manufacturing can provide consumers with various types of quality products and services with higher speed, flexibility, and efficiency. The rapid development of the new generation of information technologies, particularly mobile Internet, sensors, big data, supercomputing, industrial Internet, Internet of Things, AI, machine learning, collaborative robots, virtual reality/augmented reality (VR/AR), and other digital, networked, and intelligent technologies, provides an important technological support for the development of HCIM. As consumer demands become increasingly personalized, enterprises must adopt a user-centric approach to gain a larger market share and improve the market competitiveness and continue to meet personalized consumer demands through the application of advanced technologies and changes in the model of organizational management. Therefore, to meet diversified market demands, considering the economic viability of technologies, employment, and other factors, the "human-centered" concept must be a guiding principle in promoting intelligent manufacturing.

(2) Humans have a critical role in the implementation of intelligent manufacturing. Industrial robots are one of the important components of intelligent manufacturing, while traditional industrial robots, owing to certain

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weaknesses, are yet to fully meet the new demands in the market. For example, the deployment of traditional robots is very expensive, and individual robots, which still require the support of numerous peripheral devices, cannot be used directly in the production line of a factory. Although robots are highly flexible, the flexibility of the entire production line is generally low. In addition, small and medium enterprises (SMEs), owing to financial constraints, are incapable of transforming substantially to their production lines. They are also more sensitive to the return on investment of their products. The robots are required to have a low overall cost, rapid deployment, and convenient operation. However, traditional robots are not yet able to provide a satisfactory solution at a manageable cost. If humans are responsible for the work processes that require flexibility, tactility, and agility, while robots use their advantage of speed and accuracy for repetitive and standardized work processes, such type of human–machine collaboration would provide a fairly good solution for SMEs. In addition, if robotic technologies are used to strengthen the workforce, which would in turn lead to reduced costs and better competitiveness, it can also create more jobs for our society.

(3) Humans will have a more important role in the future development of intelligent manufacturing. The actual demands for intelligent manufacturing vary between industries and enterprises. Notably, not all industries and factories need to be completely automated or completely unmanned. Therefore, the technical and economic viability should also be considered in promoting intelligent manufacturing. For example, unlike the automotive industry, the aviation, aerospace, shipping, and construction industries, owing to the complexity of their tasks and processes, have not yet realized full automation and unmanned production. They are still mostly dependent on human–machine cooperation, accumulation of human knowledge and experience, as well as self-motivation of humans. Therefore, the future of manufacturing is not to build purely unmanned factories, but to allow people to engage in more valuable and enjoyable work with the support of advanced technologies and simultaneously generate higher economic returns for the enterprises.

3 Contents and technology system of HCIM

HCIM applies the human-centered principle in the whole lifecycle of an intelligent manufacturing system (including design, manufacturing, management, sales, and services), fully considers the various factors (physiological, cognitive, organizational, cultural, social, etc.) concerning humans (designers, producers, managers, users, etc.), and uses advanced digital, networked, and intelligent technologies to promote the human–machine collaboration in a manner that leverages their comparative advantages in completing various tasks, thus achieving the best results in improving the production efficiency and quality, ensuring the physical and mental health of the involved personnel, satisfying user demands, and promoting a sustainable social development.

HCIM represents an important development approach and key direction for intelligent manufacturing in the future. HCIM is not limited to any single manufacturing model or paradigm. In the process of its development, numerous models and forms, such as shared manufacturing, social manufacturing, and sustainable manufacturing, have emerged or will emerge. The research on HCIM is still at its infant phase, but it can be expected that its definition, contents, and characteristics will continue to evolve and expand.

3.1 Human factors in intelligent manufacturing

From the perspective of the full life cycle of intelligent manufacturing [6], human factors in intelligent manufacturing include human roles, human–machine relationships, physical ergonomics, cognitive ergonomics, and organizational ergonomics (Fig. 1), which are described below.

3.1.1 Role of humans

The role of humans is mainly reflected in their different roles, functions, and types of work in intelligent manufacturing systems. From an intelligent perspective, the role of humans is centered on the creation of knowledge and processes, through the continuous accumulation and practice of human experience, talent, and knowledge so that the intelligence of manufacturing can be constantly optimized and improved.

Scholars have analyzed the critical status and defining role of humans and importance of human factors in intelligent manufacturing and concluded that, by integrating and synergizing advanced technologies, humans and organizations can truly implement their role and generate benefits [7,8]. Zhou et al. [1,2] proposed the concept of

HCPS and underscored the dominant role of humans in HCPS: both physical and cyber systems are designed and created by humans. The models, methods, and guidelines for analysis, calculation, and control are determined and embedded into the cyber system by research and development (R&D) personnel. The purpose of the whole system is to serve humans. Humans are both designers, operators, supervisors, and beneficiaries of the services provided by the intelligent manufacturing system [6]. In its report on the Industrial Internet, General Electric defines humans as a key factor in the Industrial Internet [4]. Nunes et al. [9] argued that the role of humans in the cyber–physical system (CPS) includes data acquisition, state inference, drive, control, and monitoring. Madni et al. [10,11] reported that the role of humans in HCPS includes monitoring of nonhuman-in-the-loop, monitoring guidance of nonhuman-in-the-loop, and control of human-in-the-loop. Jin et al. [12] summarized the role of humans in HCPS as operators, agents, users, and sensing terminals.

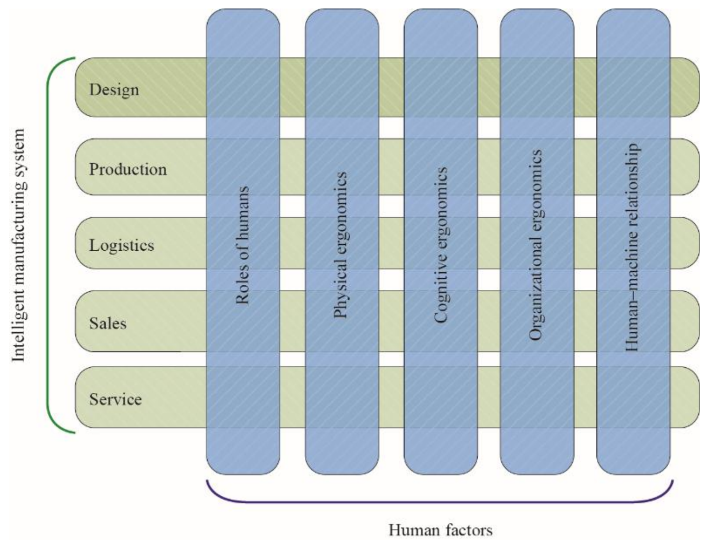

Fig. 1. Intelligent manufacturing system and human factors.

3.1.2 Human–machine relationship

In the process of production and life, humans are constantly involved in the transformation of the nature, society, and themselves and build connections with the objects of labor and tools of production, which includes human–machine interaction and cooperation, which is referred to as human–machine relationship. The studies on human factors in intelligent manufacturing systems often involved analyses on human–machine relationships. Classic examples of international research on human–machine relationships include the studies on human–robot relationships, Operator 4.0, human–CPS relationship, and human-centered intelligent manufacturing system. For example, Romero et al. [13] proposed the concept of Operator 4.0 in the context of HCPS and envisaged its potential benefit to human–machine symbiosis and sustainable manufacturing. The contents of Operator 4.0 include analytical, AR, collaborative, health, intelligent, social, super-strong, and virtual operators [14].

The irreplaceable role of humans in intelligent manufacturing systems is underscored in studies carried out by both Chinese and foreign researchers, which also shows the importance of studies on the role of humans and human–machine relationships in intelligent manufacturing systems. With the further application of intelligent manufacturing, the role of humans in the system will gradually shift from “operator” to “supervisor” and humans will become the most dynamic factor affecting the manufacturing system. Considering the limit of labor forces and increasing labor costs, it is necessary to optimize the staffing and improve the match between manual control and machine operation to achieve an efficient collaboration.

3.1.3 Human factor engineering/ergonomics

Human factor engineering/ergonomics refers to the comprehensive use of the research methods and means of physiology, psychology, computer science, system science, and other disciplines for the study on the interrelationship between humans, machines, their working environment, and law of influence, to achieve the goal

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of improving the system performance and ensuring human safety, health, and comfort [15], including physical ergonomics, cognitive ergonomics, and organizational ergonomics.

Human factor engineering/ergonomics have three main areas of research. (1) The subjects of traditional human ergonomics research include work posture, repetitive motions, workplace layout, work-related illnesses, and employee safety. In intelligent manufacturing systems, the main areas of physical ergonomic research include partial automation, human safety, and wearable devices. [16]. (2) Cognitive ergonomics focuses on mental processes. Its subjects of research include brain load, decision making, work stress, human reliability, and skill performance. In the context of intelligent manufacturing, the main research progress includes VR integration, reducing cognitive stress with information technology, and technology reserves [17–19]. In addition, technological advances in areas such as perception, simulation, AI, cloud computing, big data, and digital twins, which are also aimed to enhance or simulate the enhancement in various cognitive abilities of humans, are also in the scope of cognitive ergonomics. (3) Organizational ergonomics focuses on the optimization of socio-technical systems, including work design, human resource management, teamwork, virtual organization, and organizational culture. In the intelligent manufacturing system, the related research progress includes flattening organizational structure, updating work design methods, and industry–user integration.

3.2 Technology system of HCIM

Based on the HCPS theory, this study proposes a three-tiered reference architecture for HCIM. As shown in Fig. 2(a), the architecture consists of unit-level intelligent manufacturing, system-level intelligent manufacturing, and system-of-systems-level intelligent manufacturing. Among them, the technology system of unit-level intelligent manufacturing is shown in Fig. 2(b), which includes mainly machine intelligence technologies (e.g., intelligent perception, intelligent decision-making, intelligent control, learning, and cognition), manufacturing domain technologies (e.g., cutting and processing, welding, and additive manufacturing), and human–machine collaboration technology/human–machine relationship. On the basis of unit-level intelligent manufacturing, system-level intelligent manufacturing and system-of-systems-level intelligent manufacturing systems (e.g., intelligent workshops, intelligent production lines, and intelligent factories) can be constructed through technologies such as industrial network integration, Internet of Things, intelligent scheduling, Industrial Internet, and cloud platforms, to realize the optimized allocation of manufacturing resources and human resources on a larger scale.

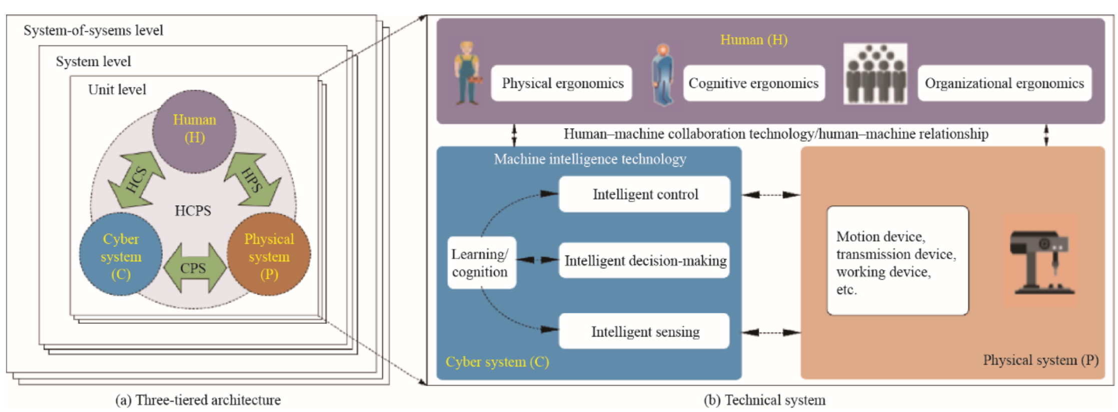

Fig. 2. Illustration of the technology system of HCIM [2,3,5].

Note: HPS: human–physical system; HCS: human–cyber system.

In the HCIM system, the role of the cyber system is to carry out the necessary perception, cognition, analysis, decision-making, and control of the physical system together with humans, so that the physical system (machine, processing, etc.) could run in the best possible manner, including the cognitive level, decision-making level, and control level of human–machine collaboration, but also the ergonomics of the human body, cognitive ergonomics, organizational ergonomics, etc., need to be considered. Particularly, technologies related to HCIM include human-centered design, control, AI, computing, automation, service, and management. Among them, human-centered design is also referred to as “participatory design”. Focusing on the thinking, emotion, and behavior of humans in the design process, it provides an innovative approach of problem solving. It focuses on the needs of the end user and places them at the center of the digital design process. Human-centered AI stresses that the development of AI should be guided by the impact of AI on the human society and further incorporate the diversity, variability, and depth of human intelligence to enhance human skills rather than replace them.

4 Practical applications of HCIM

HCIM is a general system that can be understood from four dimensions: product, production, model, and foundation. Among them, human-centered intelligent products are the main subject, human-centered intelligent production is the main line, human-centered industrial model is the main theme, and HCPS and human factor engineering are the foundations (Fig. 3). Based on the discussion on human factor engineering and HCPS in the above sections, the following sections focus on the application level and discussion on human-centered intelligent products, human-centered intelligent production, and human-centered transformation of industrial model.

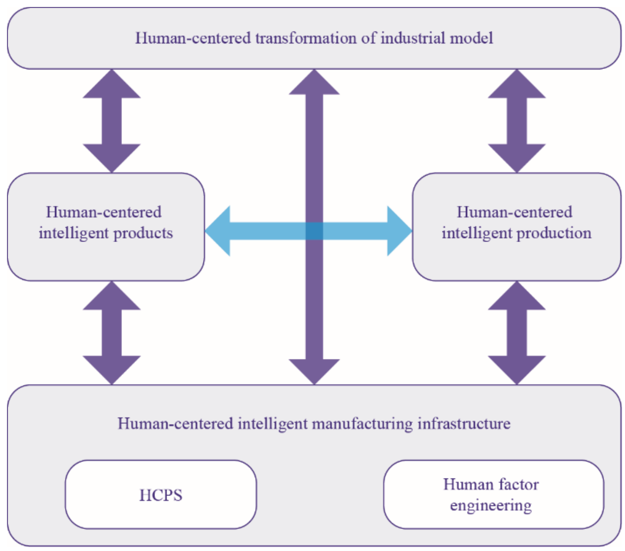

Fig. 3. Four dimensions of HCIM.

4.1 Human-centered intelligent products

Products and manufacturing equipment are the main subjects of intelligent manufacturing. Among them, products contain the values of intelligent manufacturing, while manufacturing equipment is the premise and basis for intelligent manufacturing. In this context, the concept of “human-centered” implies that intelligent products and equipment, particularly products directly facing large groups of consumers, should fully consider the needs of humans and human factors at the beginning of the design process. In the design of intelligent industrial equipment, possible human intervention should also be considered to provide the necessary mandate and space for designers.

Case 1*: A famous mobile phone brand*. The “Internet-based development” model championed by this brand introduced a new trend of “creator-led” designs. It has become one of the fastest-growing companies in terms of sales, exceeding 170 billion CNY in 2018. Under the “Internet-based development” model, the R&D team gathers user demands through Weibo, WeChat, BBS, and other channels to improve their products. As much as 80% of the update needs of the mobile phone system originate from the suggestions of netizens, while 33% of the updates in the operating system are developed directly by users [1].

4.2 Human-centered intelligent production

The development of digitized, networked, and intelligent manufacturing industries is an enabler for both product and technology innovation. It turns the manufacturing industry into an intelligent integrated manufacturing system. In this process, it is necessary to follow a human-centered approach, comprehensively improve the design,

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manufacturing, and management of products, and promote the building of intelligent enterprises. The application of human-centered intelligent production includes human–machine design cooperation, human–machine collaborative assembly, and human-centered production management. Intelligent optimized design, intelligent collaborative design, and "crowd design" based on group intelligence are important elements of the human-centered intelligent design. The development of an intelligent design system based on HCPS is also an important element in the development of HCIM.

Case 2*: Human-machine design cooperation based on deep learning*. Raina et al. [20] of Carnegie Mellon University extracted human design strategies and implicit rules through deep learning to teach machines how to assist humans in their design activities. Raina et al. [21] attempted to model the migration process of humans and proposed a probabilistic model on this basis. The model is successful in transferring the experience migration strategies of humans onto machines, so that they can be more effective in helping humans with their designs.

Case 3*: Human-machine collaborative assembly*. As robots cannot be fully deployed in certain industries or processes, a team led by Professor Lihui Wang at Royal Institute of Technology carried out a study on human–machine symbiosis in assembly (SYMBIO-TIC) with the funding support of Horizon 2020, the European Union's research framework program. With a focus on human–machine collaborative assembly, the project's key subjects of research include sensing and communication, active collision avoidance, dynamic task planning, adaptive robot control, and mobile worker assistance, with the aim of ensuring worker safety and efficient human–machine collaboration. The team has already worked with several automotive and robotic companies to promote the application of the project [22].

Case 4*: Lean model*. Professor Jeffrey Liker from University of Michigan, cofounder of Technology Management, Lean Manufacturing, Lean Product Certification, and other courses, defines the essence of the "lean model" as "continuous improvement and respect for people." The essence of respecting people is to place people first, which implies commitment to corporate culture, full participation, standardization, developing outstanding talents and teams who believe in the company's philosophy, making continuous reflection and continuous improvement, and building a learning organization. As the "lean model" suggests, the human-centered management is an important development strategy for enterprises, and humans are the source of vitality and creativity and most valuable resource of enterprises.

4.3 Human-centered transformation of industrial model

The industrial model transformation focuses on intelligent services is the main theme of HCIM. With the promotion and application of advanced technologies, the manufacturing industry will go through a transformation from product-centric to user-centric, from large-scale production on the assembly line to customized production, and from production-oriented manufacturing to service-oriented manufacturing.

Case 5*: Industrial Internet platform of a household appliance company*. Unlike traditional manufacturing and other e-commerce platforms, the platform in this case follows a human-centered and build-to-order approach. The users of the platform are involved in the entire process from product interaction, design, and procurement to manufacturing and services. As they use the products, they can get constant iteration and interaction through "net devices" (as opposed to the traditional concept of "electrical appliances"). The enterprise gauges user demands through product interaction, turning a closed enterprise into an ecosystem, so that users, enterprises, and resources can create values in the whole process. It turns users into voluntary contributors to the growth of the product, increases the benefits for the enterprise, and allows the enterprise to replicate its development model in the industry. For example, the platform has cooperated with a local enterprise to establish an industrial base of building ceramics, consolidating more than 130 companies that were "fighting on their own" into 20 companies. After transformation and upgrading, the manufacturing cost was reduced by 10% and the production capacity increased by 20%. Thus, the human-centered transformation of industrial models has delivered real benefits for both users and enterprises [3].

5 Reflection and suggestions

5.1 Policy level

In recent years, the European Union, the United States, Japan, and other countries and regions have attributed a high importance to the research on HCIM. For example, the United States have launched a forward-looking program in this field referred to as Future of Work at the Human–Technology Frontier (FW-HTF), which brings both challenges and inspiration for HCIM development in China. We hereby suggest incorporating HCIM into relevant national strategies in a timely manner and strengthening the top-level design. In the pilot demonstration, application promotion, publicity and implementation, education, and training of intelligent manufacturing, the human factors should be fully considered and the human-centered concept should be integrated into the standard setting and maturity evaluation of intelligent manufacturing systems. In the meantime, more attention should be devoted to the standardization of human–machine collaboration, human–machine task division, and maturity evaluation of intelligent manufacturing personnel. This will help concepts such as HCPS and human factor engineering take root in the practice of intelligent manufacturing and promote HCIM's development in China.

5.2 Enterprise level

From a human-centered perspective, it is imperative for intelligent manufacturing companies to consider and address the following two issues: (1) how to use advanced and appropriate technologies to prolong the career of employees, so that those employees whose physical strength is declining while still at the peak of their intelligence and experience can continue to create values for the company with the support of technology and (2) how to use technology to create an environment where the younger generation is willing to work in the manufacturing industry and feel the joy of working and creating value through intelligent manufacturing. We suggest that manufacturing companies employ the "human-centered" approach as an important principle in the development of intelligent manufacturing, devote more attention to employee training, education, and management, and regard it as a strategic investment for the company. Simultaneously, companies can better use collaborative robots to meet their demands, rather than replacing all humans with traditional robots. Through repeated trials and adjustments, they will be able to find the most appropriate manner of human–machine collaboration for their companies to increase the productivity and profits.

5.3 Research level

At the research level, more research efforts are needed on HCPS, human-centered intelligent manufacturing, human factor engineering for intelligent manufacturing, collaborative robotics, and other subjects. It is important to devote more attention to the construction and improvement in the science and technology system of HCPS and promote the application of HCPS in the field of intelligent manufacturing, i.e., human-centered intelligent manufacturing. The research on HCIM theories and applications should include human-centered design, products, automation, AI, production, factories, and services. Simultaneously, more emphasis should be placed on the studies on human ergonomics, cognitive ergonomics, organizational ergonomics, and other subjects of human factor engineering to achieve a positive interaction between natural and social sciences. In addition, collaborative robots and tri-co robots (i.e., coexisting, cooperative, and cognitive robots) are important directions for future research. The interactions within the HCPS, human digital twin, and human-in-the-loop are research topics that need to be strengthened.

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