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TOPICAL REVIEW

Intelligent Manufacturing From the Perspective of Industry 5.0: Application Review and Prospects

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ABSTRACT While Industry 4.0 improves human productivity, it also raises sustainability and social challenges. Industry 5.0, as a supplement and logical continuation of the Industry 4.0 paradigm, focuses on the development of a human-centric, sustainable, and resilient manufacturing system. This paper reviews the existing literature. First, it discusses the definition and implementation framework for Industry 5.0. Then, it expounds the application status of Industry 5.0 in the field of intelligent manufacturing from four perspectives: digital manufacturing and intelligence, human-centric intelligent manufacturing and production process management, decentralized and resilient production, and sustainable production. It summarizes the role of Industry 5.0 technology in various intelligent manufacturing scenarios, as well as the challenges it faces, and concludes by analyzing Industry 5.0's potential development direction and future technologies. This paper believes that the application of Industry 5.0 technology will effectively improve the production capacity of intelligent manufacturing systems and promote the development of intelligent manufacturing systems in a safe, efficient, sustainable and resilient direction; the development of Industry 5.0 will focus on giving full play to human creativity, avoiding repetitive labor through human-robot collaboration, and thereby realizing human value.

INDEX TERMS Industry 5.0, intelligent manufacturing, digital twin, Internet of Things, human–robot collaboration.

I. INTRODUCTION

Since its inception, Industry 4.0 has been considered to be technology-driven, with machine learning providing interconnected control between production equipment in order to change the production process and improve production efficiency [1]. For this reason, Industry 4.0 often focuses on increasing economic benefits and expanding production scale to meet customer demands in production practice, while ignoring the role of workers. As a result, some inhumane production strategies implemented by companies to reduce labor costs have raised concerns among workers, society, and even the government [1]. In addition, Industry 4.0 has introduced a large number of industrial robots into the production process, but has objectively squeezed out most jobs [2], resulting in a decrease in employment, workers and trade unions opposing robots, and further deteriorating the relationship between humans and robots. The issues in Industry 4.0 can be analyzed primarily through three lenses: human factors, sustainability, and resilience.

From the perspective of human factors, although the implementation of Industry 4.0 integrates various advanced technologies, its core concept of improving production efficiency and economic benefits still results in a large number of workers engaging in monotonous and repetitive labor. These new technologies often ignore the human factor, not only failing to help employees reduce stress but also exacerbating their physical and mental fatigue [3]. The new work patterns and technological demands brought about by Industry 4.0 often cause difficulties for workers, many employees are dissatisfied with technological advancements and the new skills they require, reject external control of computer systems, or are fearful of technology and its associated changes [4]. In addition, the excessive supervision of individ-

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TABLE 1. Impact of industry 4.0 on sustainability [6].

	Micro	Meso	Macro
Economy	↑	↑	—
Environment	↑	↑	—
Society	↓	—	↓

Where ↑ indicates a positive impact, ↓ indicates a negative impact, and - indicates controversy.

ual employees in Industry 4.0 has also led to resistance from workers [5].

From the perspective of sustainability, Industry 4.0's impact on the economy and environment is mostly positive at the micro and meso levels, but controversial at the macro level; however, its impact on social sustainability is generally negative [6]. Scholars' evaluation of Industry 4.0 in terms of sustainability is summarized in Table 1.

Resilience is dependent on humans and does not appear prominently in academic discussions of Industry 4.0. However, in recent years, supply chain disruptions caused by increasingly complex global supply networks, natural disasters, political interference, and other factors [7], as well as the serious impact of the COVID-19 epidemic on traditional industrial industries [8], all reminded us of the importance of resilience in the future industrial production system to quickly control the various drastic changes and emergencies that may occur [9].

Industry 4.0 focuses on integrating digital technology into the production process in order to achieve better results and maximum profits in production. This completely profit oriented approach is unsustainable [10] and also lacks consideration for human factors. Therefore, Industry 5.0 expands its focus to human and society, energy efficiency, and environmental aspects in the workflow [11]. Industry 5.0 proposes intelligent manufacturing with humans at the core, using robots to complete repetitive mechanical labor while workers are responsible for more creative tasks such as customization and criticism. This further utilizes human brainpower and creativity to improve process efficiency [12], optimize human-machine relationships, and enhance the sustainability and resilience of manufacturing systems. It is expected to solve the aforementioned problems in the future. Industry 5.0 is a supplement and logical continuation of the Industry 4.0 paradigm [13]. The similarities and differences between the concepts of Industry 4.0 and Industry 5.0 are summarized in Table 2.

II. THEORIES RELATED TO INDUSTRY 5.0

A. DEFINITION OF INDUSTRY 5.0

The theoretical system of Industry 5.0 is still in its early stages, and its definition remains unclear. The European Commission (EC), the proponent of Industry 5.0, pointed out that Industry 5.0 is a forward-looking concept about the future of the industry, aiming for a human-centric, sustainable, and resilient manufacturing system [9]. According to reference [20], Industry 5.0 is a human-oriented design solution in which ideal human companion and collaborative robots collaborate with human resources departments to achieve personalized autonomous manufacturing through enterprise social networks, allowing humans and robots to work together. Collaborative robots are not programmable, but they can detect and recognize human presence. In this case, collaborative robots are used for repetitive tasks and labor-intensive work, while humans are in charge of customization and critical thinking. Workers no longer adapt to machine requirements as they once did, but rather design machines to recognize users, extract behavioral characteristics such as users' skills and preferences, and make appropriate adjustments [21]. The focus of the definitions of Industry 5.0 proposed by different scholars is summarized in Table 3.

Based on the definitions provided by the aforementioned scholars, we can conclude that Industry 5.0 incorporates humans into the production system, fully utilizes the creative value of human intelligence, and employs robots to assist people in developing a more advanced and efficient production model. In this process, the welfare of workers is guaranteed, and their skills are improved.

B. INDUSTRY 5.0 IMPLEMENTATION FRAMEWORK

The implementation framework identifies the support on which Industry 5.0 is based, as well as the constraints that must be met during the application process. The European Commission believes that Industry 5.0's paradigm shift is founded on three core principles: sustainability, resilience, and, most importantly, human-centricity [30]. Sustainability requires reducing the damage caused by industry to the self-heating environment and ensuring the long-term development of mankind; resilience emphasizes the environmental adaptability and impact resistance of industry to cope with possible drastic changes in the external environment; human-centricity is the core of Industry 5.0, which puts human welfare at the center of the production process [31], aiming to realize human value under the premise of ensuring health and safety. The basic framework of Industry 5.0 [32] is shown in Fig. 1.

On this basis, Leng et al. [13] proposed a basic system framework for realizing Industry 5.0 based on the three dimensions of technology, reality, and application, as well as an overview of the research status of these three aspects, discussed the key enablers, realization paths, and potential future applications of Industry 5.0. Lu et al. [33] introduced the Industry 5.0 manufacturing framework, which consists of two levels: manufacturing system and machine, and defined and classified human needs and motivations in manufacturing, helps the formation of efficient human-machine teams and flexible manufacturing processes, and promotes human-machine collaboration while safeguarding human well-being. Ivanov [34] developed the framework for Industry 5.0 using a feasible supply chain model, a reconfigurable supply chain, and a human-oriented ecosystem, revealing the key characteristics of Industry 5.0 as a technical organizational framework, such as technical principles, coverage areas, levels, and bottom lines. This contributed to the con-

TABLE 2. Differences between the concepts of industry 4.0 and industry5.0.

	Industry 4.0	Industry 5.0
Human-centricity	Lack of attention to the human factors [14]	Pay attention to workers' safety, interest, fatigue level, etc.
	Produces boring, repetitive work	Focus on realizing the value of workers at work
	Smart machines control factories and take over workers' jobs [15]	Workers and smart machines work together [16]
Sustainability	The energy intensity of underlying technologies accelerates environmental degradation [17]	Use sustainable energy and improve energy efficiency
		Maintain a balance between economic growth and social and environmental development [18]
Core concept	Technology-driven [19]	Value-driven
	Focus on productivity-driven economic growth	Focus on economic circularity, environmental sustainability, human-centricity, social values , and long-term resilience

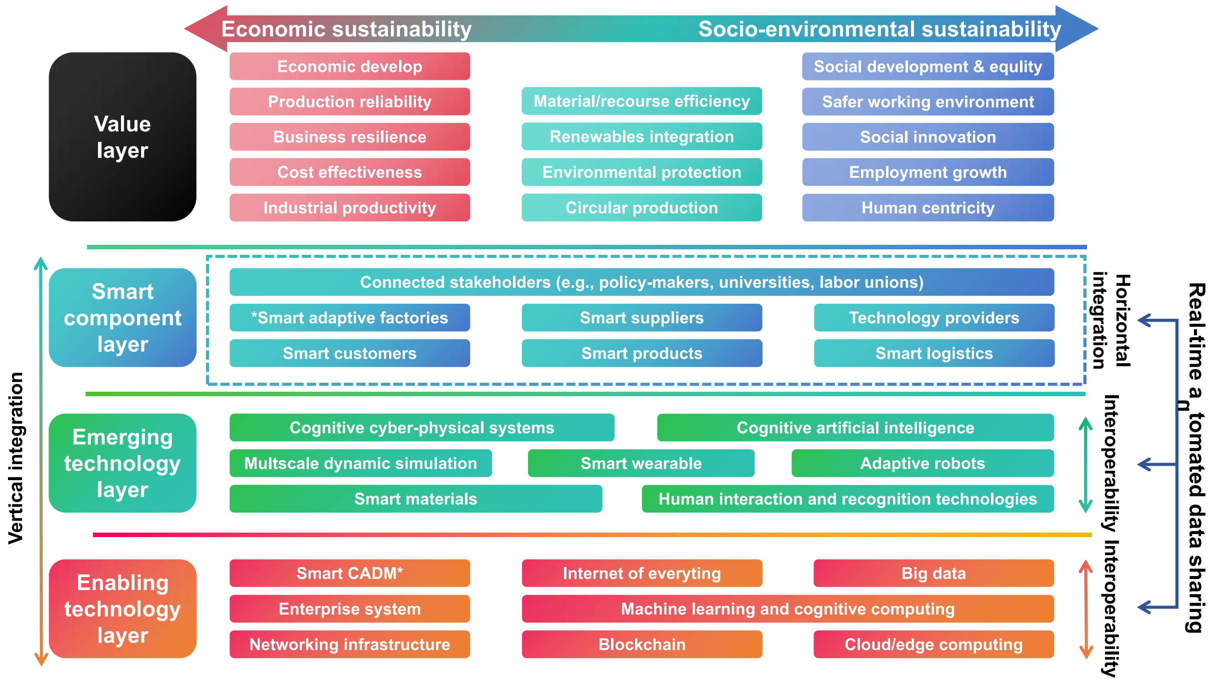
TABLE 3. Summary of industry 5.0 definitions.

Ref	Year	Focus points
[22]	2021	Creativity of humans, safety of production
[23]	2022	Seamless sharing of work between humans and robots
[24]	2022	Human-centricity, production process restructuring
[18]	2022	The ability of industry to achieve social goals while achieving growth, placing humans at the center of the production process
[25]	2022	Humans and robots working together, improve the efficiency of industrial production and productivity in manufacturing
[26]	2023	Placing humans at the center of the production process, leveraging human advantages, humans control technology
[27]	2023	Innovation, sustainable production, combining automation advantages with human creativity
[28]	2024	Improved efficiency, worker welfare, human creativity, personalized customization
[29]	2024	Humans and robots work together, relying on smart machines to increase resilience and sustainability, enhance human capabilities

ceptualization of Industry 5.0 and clarified the necessary rules to be followed in the specific implementation of Industry 5.0. Sindhwani et al. [35] proposed a framework for analyzing the driving factors of Industry 5.0 in order to achieve sustainable development, and they believe that personal customization is the highest priority standard for realizing Industry 5.0. The Manufacturing Execution System (MES) framework proposed by Masoud et al. [36] helps small and medium-sized enterprises improve their production processes, and the effectiveness of the framework has been demonstrated through case studies, demonstrating the technological advantages of Industry 5.0. Although these frameworks are applicable to different scenarios, they all analyze and expand around the core concepts proposed by Industry 5.0, providing a reference for the implementation of Industry 5.0 in various fields. In addition, in the specific implementation process, scholars have also proposed corresponding frameworks for the various enabling technologies of Industry 5.0 from different perspectives, such as the digital twin framework for incorporating humans into digital systems [37], the task allocation framework for promoting human-robot collaboration [38], and the data protection framework for ensuring the elasticity of Industry 5.0 [39], in order to meet their specific needs. This part will be introduced in detail in Section III.

III. APPLICATION PERSPECTIVE

This section will discuss the impact of the three core concepts of Industry 5.0 and its related technologies on



*CADM: Computer-aided design and manufacturing technologies.
**Smart factories could be replaced with other smart entities depending on the industrial context.

FIGURE 1. Basic framework of industry 5.0 [32].

intelligent manufacturing from the perspective of digitalization manufacturing and intelligence, production process management, and decentralized production. The relationship between them is shown in Fig. 2. Among them, technologies for Industry 5.0 such as Human Digital Twin (HDT) and Human-Robot Collaboration (HRC) change the existing production process management methods by introducing humans into production; technologies such as Decentralized Autonomous Manufacturing (DAM) and Industrial Internet of Things (IIoT) provide a more flexible decentralized production method for intelligent manufacturing; technologies such as Green Internet of Things (G-IoT) and Sustainable Supply Chain (SSC) improve the energy utilization efficiency of the aforementioned other technologies, making intelligent manufacturing more sustainable. In addition, the application of these technologies will promote the development of intelligent manufacturing in the direction of intelligence and digitalization.

A. DIGITAL MANUFACTURING AND INTELLIGENCE

Digital twin technology is regarded as the foundation of future manufacturing [40], and using digital twins to promote seamless collaboration between humans and robots is a key feature of Industry 5.0 [20]. Visualizing various types of data for decision-makers in a digital twin environment can also help them make better decisions [41], resulting in increased corporate efficiency [42]. Modeling is one of the challenges that digital twins face during the Industry 5.0 revolution [43]. Lightweight digital twin models can often quickly implement a two-way feedback process [44]. Marchi and Baalbergen [45] introduced an operator-centric digital twin model and investigated the key components of operator-customized digital twin architecture, which aids in the transition from Industry 4.0 to Industry 5.0 implementation. The scalable IIoT platform introduced by Montini et al. [46] provides ideas for standardizing the creation of digital twins. This platform has advantages in creating customized data representations of production systems and digital twin instantiation.

The combination of the digital twin, Internet of Things (IoT), extended reality, and other technologies has greater application potential for process optimization and decision-making enhancement [47], [48]. Awouda et al. [49] proposed the IoT Architecture Reference Model (IoT-A or IoT-ARM) as a benchmark for designing and implementing an IoT architecture with a focus on the digital twin. The application of blockchain makes it possible to use smart contracts for information management and access control, thus providing a solution to the information security issues of digital twins [50], [51]. Machine learning-driven digital twin technology has significant advantages in the life cycle management of complex equipment [52]; the cooperation between explainable artificial intelligence and digital twins improves the robustness, predictability, and maintainability of the manufacturing process [53]; embedded digital twins can enhance the intelligence of cyber-physical systems and promote the integration of data access, monitoring, and other functions [54]. Fig. 3 depicts how digital twins with other technologies in smart manufacturing.

The Industry 5.0 paradigm aims to create efficient and adaptable production systems by combining human intelligence with cutting-edge technologies such as the Internet

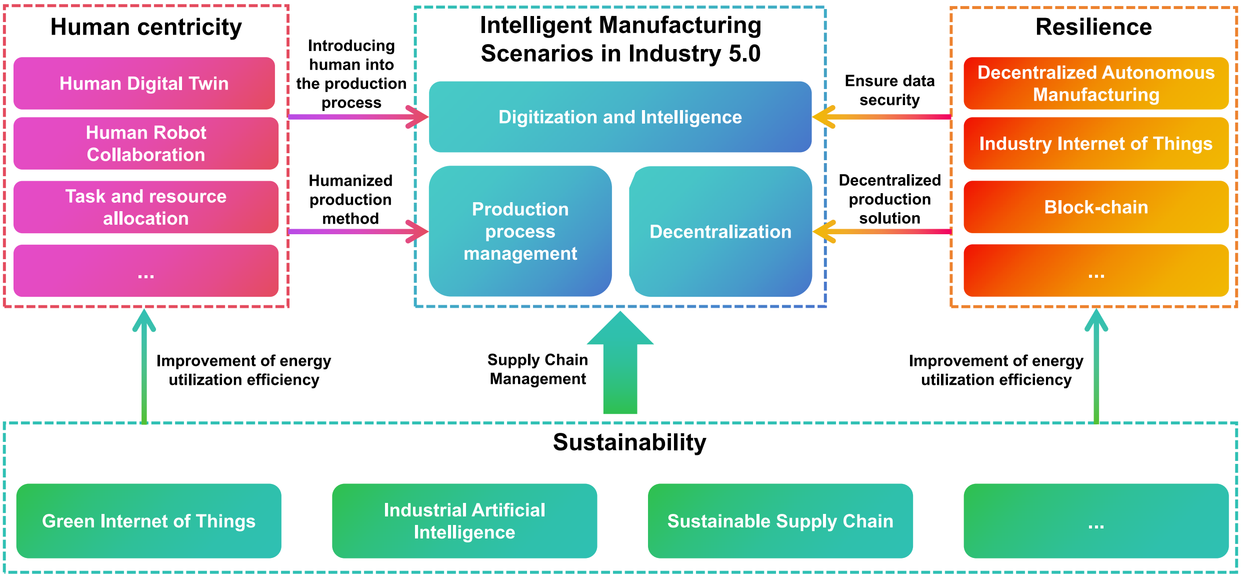


FIGURE 2. The impact of industry 5.0 related technologies on intelligent manufacturing.

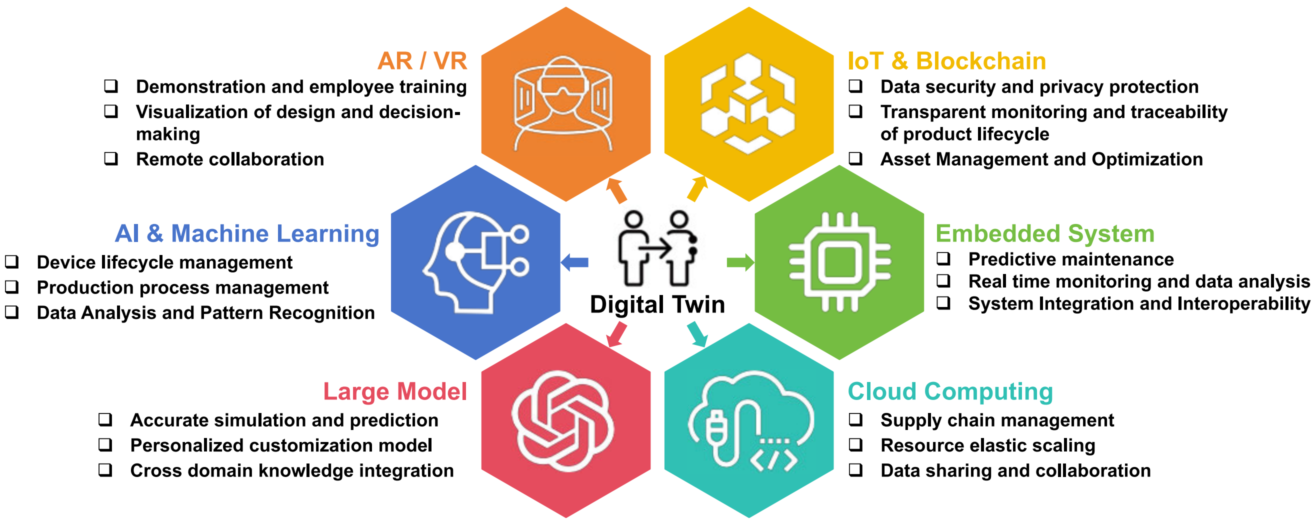


FIGURE 3. Integration of digital twins with other technologies.

of Things, artificial intelligence, and robotics [55], [56], and its effectiveness has been experimentally validated [57], [58], [59]. Abuhasel [60] used a zero-trust network-based access control scheme to extend support for operating devices while decreasing failures. Zong et al. [61] proposed a high-performing IIoT cross-regional end-to-end transmission control scheme for ensuring the continuity and stability of intelligent machine production in emergency communications. The AIaCM architecture [62] deeply integrates technologies such as artificial intelligence, IoT, and edge computing into the manufacturing industry, potentially supporting large-scale customized manufacturing. Its architecture is roughly depicted in Fig. 4. Pattnaik et al. [63] proposed a real-time location monitoring system based on the 6G Internet of Things, with low-power Bluetooth for underground communications. The sparse attention scheme improves noise reduction performance for the voice user interface (VUI) and demonstrates the application potential of VUI in Industry 5.0 [64].

Industrial edge computing, as a key accelerator of Industry 5.0, can provide timely system insights and enable real-time decision-making [65], thereby improving manufacturing system agility [66]. By being deployed near IoT devices [67], fog-based IoT architectures can effectively handle the large amount of data generated by Industry 5.0, ensure quality of service [68], and optimize scheduling and load [69]. Fraga-Lamas et al. [70] proposed a Cyber-Physical Human-centered System (CPHS) that processes thermal images and improves operator safety by combining a hybrid edge computing architecture with intelligent fog computing nodes. Lv et al. [71] proposed a three-layer network edge computing architecture that excels at track-

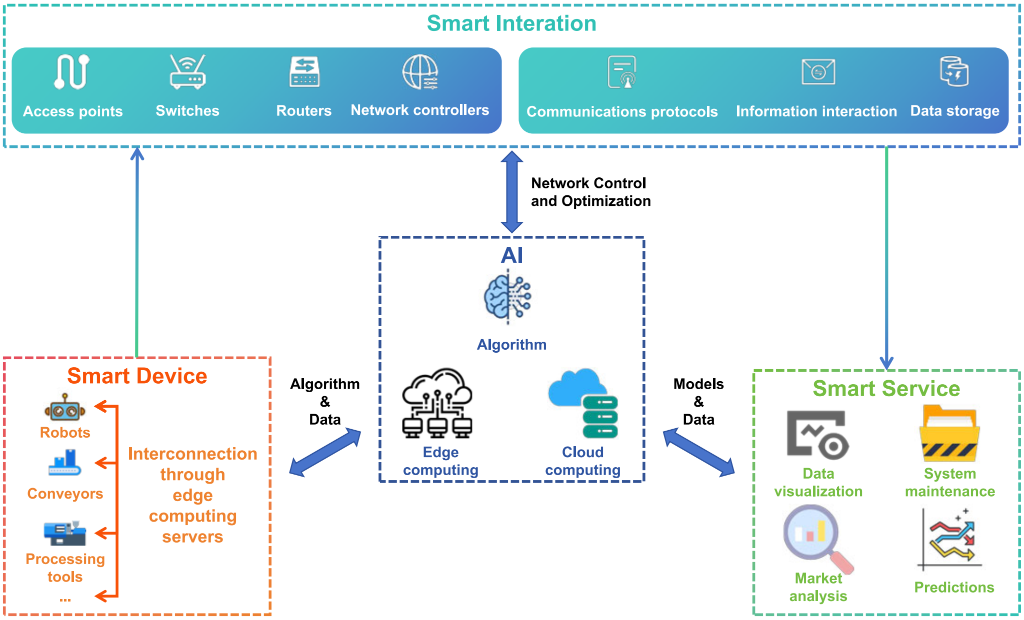


FIGURE 4. Architecture of AIaCM [62].

ing industrial gas diffusion boundaries. The web-based GUI provided by the Large-scale Edge node Management (LEM) tool allows workflow management across a large number of edge devices [72]. When used in conjunction with the corresponding federated learning algorithm, it can avoid globally sharing edge server private data [73], [74] and defend against data poisoning attacks [75].

Scholars are also interested in ways to improve the efficiency of human-robot collaborative systems. The learning from demonstration (LfD) method can help collaborative robots learn how to perform collaborative tasks alongside experienced workers while also actively teaching and/or assisting novice workers [76]. By combining machine vision with deep learning algorithms, workers' behavioral intentions can be predicted [77], and adaptive robot path planning and knowledge support can be assigned to them [78]. Spiking neural networks can be used to predict turns in assembly tasks and reduce the time it takes to recognize turns between humans and machines [79], increasing the efficiency of human-machine system assembly. In addition, Kardush et al. [80] combined the emerging time- and wave-length-division multiplexed passive optical local area network with wireless local area network technology to achieve human-machine communication deployment, which produced significant cost savings while taking into account scalability and mobility.

B. HUMAN-CENTRIC INTELLIGENT MANUFACTURING AND PRODUCTION PROCESS MANAGEMENT

To avoid repeating the mistakes of Industry 4.0, which focused on process automation and improving process efficiency [81], [82] while ignoring the role of people, HDT have been proposed as a key method to achieve human-centricity in intelligent manufacturing systems [83], [84], [85]. As a virtual replica centered on humans, HDT not only replicates their external characteristics but also weaves their internal qualities [37]. It can better monitor, evaluate, and optimize human performance [86], upgrade traditional ergonomic methods into intelligent services [87], and meet human workers' technical needs while respecting human rights [88]. Fig. 5 illustrates the conceptual framework of HDT [37].

Modoni and Sacco [89] proposed a digital twin-based framework and implementation plan that incorporates workers and their digital replicas into the digital twin loop, promotes coordinated arrangement of humans and machines through control and simulation, improves interaction between digital twins and operators, and better coordinates human-centered processes. In order to analyze the emotional state of the HDT, we may need to detect and analyze the worker's physical and mental state in real time [90]. When combined with the factory's unsafe state reasoning method based on digital twins [91], a high-fidelity digital twin workshop with workers can be built to create a safer work environment.

In addition to safety design, human-oriented digital twin technology has been applied in a variety of fields, including work management [92], robot training [93], user training [94], product and industrial design [95], etc. It will help to put humans back at the center of the production process and better reflect the value of people in the industry. The challenges digital twin faces in the implementation process, such as opacity [96], privacy information leakage [97], and network security risks [98], can be solved through technologies such as explainable AI [99], differential privacy [100], and gamification [101].

Traditional automation methods have reached bottlenecks in many production areas [102]. HRC with an understanding

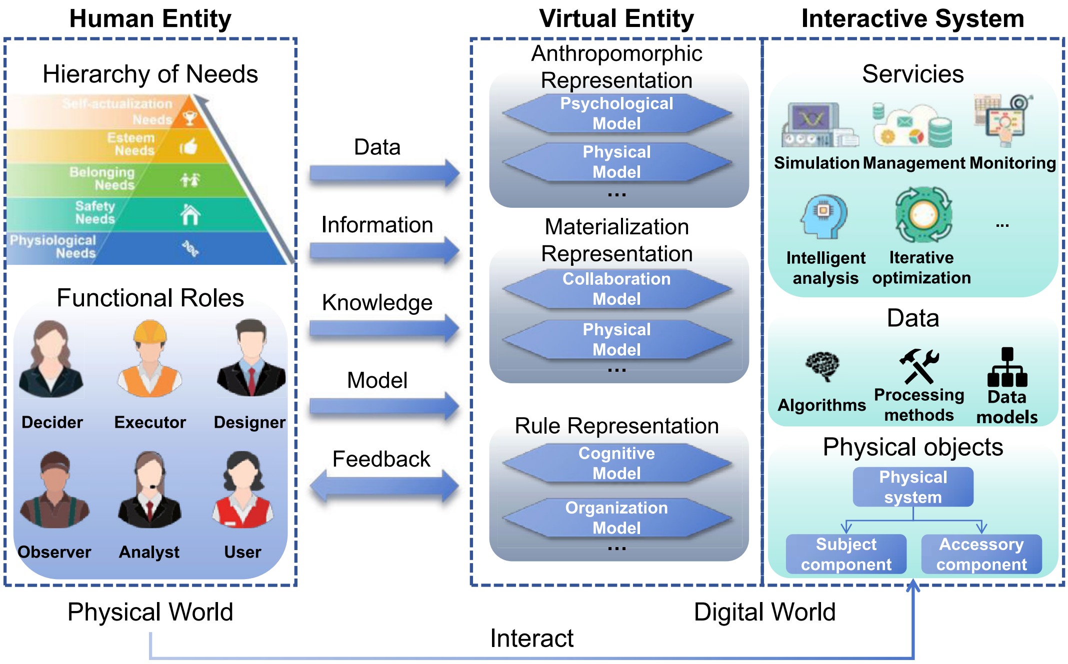


FIGURE 5. Conceptual framework of the human digital twin [37].

of difficulty and complexity is required for human-centered manufacturing and aligns with the goals of Industry 5.0 [103], [104]. Workers face a cognitive burden when dealing with complex assembly information. Scholars have proposed cognitive assistance systems based on Model-Based Definition (MBD) digital twin models [105], quality function deployment [106], and Augmented Reality (AR) [107], [108].

By optimizing task allocation and available resources, process delays can be accommodated while ensuring worker welfare [109]. This improves production efficiency and economic benefits [110], [111]. Mixed integer linear programming and constraint programming are two popular methods for balancing production lines [112]. Multi-objective task allocation models can use algorithms such as non-dominated sorting genetics [113], domain search simulated annealing [114], and hybrid gray wolf optimization [115] to solve mixed integer programming problems, balance operator psychological load [116], investment costs [117], and worker physical fitness and limitations [118], and achieve optimal task assignment. The allocation framework proposed by Kim et al. [38] analyzes process difficulty and worker ability using a heuristic algorithm to assign skilled workers to manual assembly processes, and demonstrates the improvement of productivity and operational sustainability through case studies. For mass customization scenarios, the production scheduling mechanism of Industry 5.0 [119] enables production efficiency to change exponentially with production scale. Examples show that when the number of products is greater than 600, production efficiency can surpass that of traditional customized product business, which is similar to the efficiency of mass production strategy of Industry 4.0, pointing out the direction of efficient solutions.

TABLE 4. HRC process evaluation method for industry 5.0.

Ref	Focus points
[120]	Human well-being in terms of HRC quality and stress response
[121]	Using multi-layer digital twins to evaluate the position of parts
[122]	The relationship between worker psychological load and performance in scenarios with and without robot interaction
[123]	Changes in the psychological and physiological states of workers during repeated assembly processes
[124], [125]	The impact of industrial HRC on user experience, emotional state, and stress
[126]	Human energy consumption and economic indicators under different HRC modes
[127]	The Human Psychological Model of HRC

Correspondingly, human-robot collaboration process evaluation methods for Industry 5.0 are gradually emerging. The evaluation methods developed by various scholars are summarized in Table 4.

C. DECENTRALIZATION AND RESILIENT PRODUCTION

Blockchain technology can effectively eliminate single-point failure risks in IIoT and solve security issues [128], contributing significantly to the resilience of manufacturing entities [129]. Leng et al. [130] proposed the Blockchain Smart Contract System (BSCS) ManuChain II, a digital twin of a decentralized autonomous manufacturing system, which comprehensively improves the resilience of personalized manufacturing through a series of decentralized autonomous process controls driven by a smart contract pyramid [131]. Decentralized Autonomous Organizations (DAOs) have

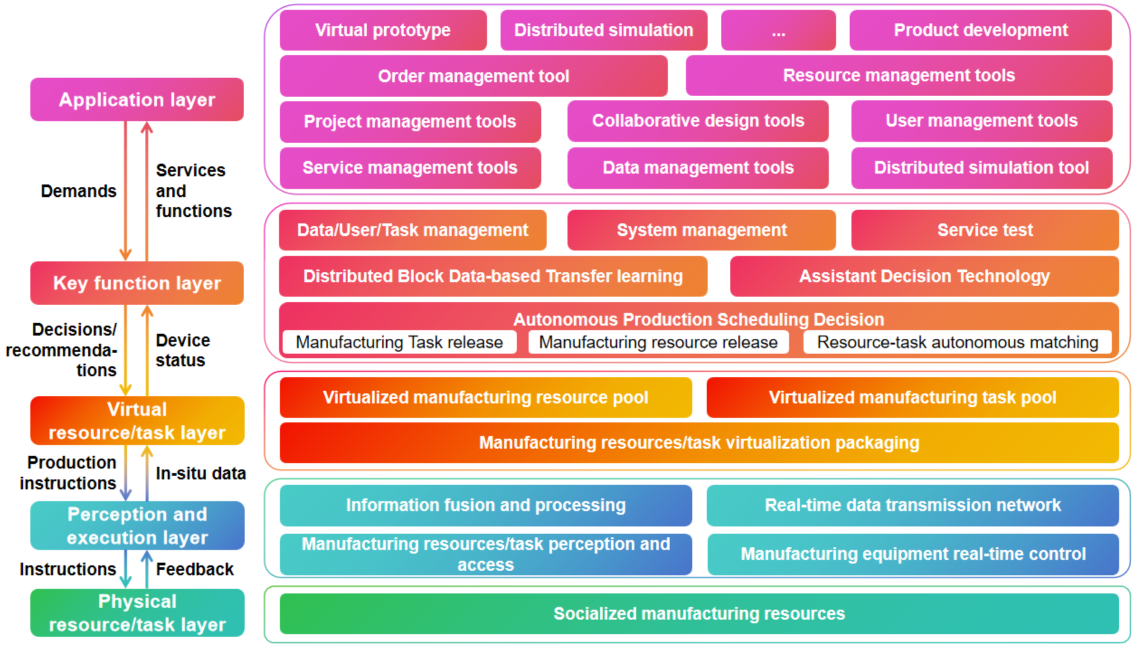


FIGURE 6. Reference architecture of DAM [133].

enormous potential for promoting the elastic manufacturing transformation of Industry 5.0 [132]. The Decentralized Autonomous Manufacturing (DAM) paradigm [133] proposed as its foundation achieves elastic production through naturally formed consensus, an open access manufacturing organization with a decentralized structure and a high degree of autonomy. Its reference architecture is shown in Fig. 6.

The resilience paradigm of Industry 5.0 relies heavily on the security of IIoT networks. Benlloch-Caballero et al. [39] proposed a novel topology-aware cognitive self-protection framework for detecting and mitigating network attacks. Combining digital twins and machine learning techniques can also detect DDoS attacks in Industry 5.0 environments [137]. Vithanage et al. [138] proposed an authentication platform that uses LDAP and MQTT technologies to improve the security and efficiency of data transmission between IoT devices. Alcaraz and Lopez [139] proposed an IIoT encapsulation protection framework that supports 6G, which can fully protect the entire 6G ecosystem, including digital twin networks. Blockchain-based secure connections are one of the characteristics of the Internet of Things that will face Industry 5.0 [140]. The trusted blockchain system provided by Babu et al. [141] ensures secure communication between edge devices while also preventing DDoS and side-channel attacks. Blockchain-based smart contracts, combined with polygonal semantic rules for data protection, can effectively prevent data leaks [142]. The FusionFedBlock solution, which combines blockchain and federated learning, protects privacy data in Industry 5.0 systems [143]. The blockchain-based Proof of Authority (PoA) trust mechanism also provides high-quality services in IIoT, including security and data privacy [144]. However, in practical applications, existing blockchain technology may not be able to ensure high throughput while guaranteeing security, making them unable to adapt to the needs of Industry 5.0, and often require sharding to improve performance [145]. In addition, challenges such as insufficient scalability, balance between security and energy consumption, and social engineering attacks faced by blockchain technology remain to be addressed [146].

D. SUSTAINABLE PRODUCTION

Sustainability is also a key component of Industry 5.0, Surveys [147] show that the Industry 5.0 model has a positive impact on sustainable performance. Turner and Oyekan [41] used Life Cycle Analysis (LCA) to evaluate emission values during the manufacturing process, providing a reference for decision-makers when making production decisions. Martín-Gómez et al. [148] used the ASTM E3012-22 standard as a sustainability indicator for industrial processes and proposed a theoretical framework for designing sustainable manufacturing systems that integrate enabling technologies, machinery, and human expertise throughout the system life cycle.

AI and IoT optimization can help improve energy efficiency significantly [149]. The Green Internet of Things (G-IoT) concept [150], [151] emphasizes the use of energy-efficient IoT hardware or software to reduce the greenhouse gas emissions of applications and services, as well as the IoT ecosystem itself [152]. Fraga-Lamas et al. [153] explored the problem of reconciling the competing visions of the Green Internet of Things and Edge AI through system design and development. The Local Data Reduction (LDR) model can address latency and cost constraints while supporting the green computing paradigm [154]. Similarly, the blockchain-based privacy protection framework can be applied to decentralize the Green Internet of Things [155]. Industrial Artificial Intelligence (IndAI) is concerned with the creation, validation, and deployment of intelligent algorithms for a variety of industrial applications with that require sustainable performance [156], [157]. The self-learning IndAI model enables manufacturing systems to achieve sustainability, meeting Industry 5.0 requirements [157]. A survey by et al. [158] shows that when new computing technologies are employed, Industry 5.0 will enable a circular economy by optimizing strategies, reducing input materials and increasing process innovation, improving economic efficiency and productivity, and reducing a company's impact on the environment. The report [159] states that the Industry 5.0 framework has led to a 1% reduction in energy use in factories with high levels of automation compared to Industry 4.0, increasing the potential for energy efficiency.

Blockchain technology not only helps to realize the elastic paradigm of Industry 5.0, but can also be combined with technologies such as digital twins and the Internet of Things to achieve continuous monitoring and verification of supply chain processes, establish a sustainable supply chain (SSC) management framework [160], and promote resource optimization and waste reduction [161]. Empirical evidence shows that blockchain technology increases supply chain transparency, reduces errors by 25%, and improves production efficiency by 15%, communication efficiency by 30%, and energy utilization [162]. However, the application of blockchain technology may face obstacles such as storage limitations, insufficient economic incentives, and high integration costs [163]. In addition to SSC, the personalized customized supply chain model proposed by et al. [164] can also reduce costs and risks and improve supply chain efficiency and sustainability.

IV. EXISTING CHALLENGES

Although Industry 5.0 technology aims to address some of the issues not considered in Industry 4.0, the current technology is not yet mature and has many shortcomings in the field of intelligent manufacturing, necessitating further development. As shown in Fig. 7, it primarily includes the following aspects.

A. DIGITAL TWIN MODELING AND DATA COLLECTION

How to establish a suitable, objective model that meets the granularity requirements has always been a challenge for digital twin technology, especially as Industry 5.0 integrates workers into the production process. The psychological load, emotional state, and fatigue level of workers in the production process are critical reference indicators for human-centered production. The digital twin model should provide accurate and objective indicators to the production system. In this process, designing the digital twin model, using the collected data to calculate the indicators accurately, and ensuring communication quality are all issues that require further investigation.

In addition, in terms of data collection for digital twin models, additional wearable data collection devices may elicit worker resistance and add psychological burdens, whereas excessive collection of private information may cause workers to lose trust in the production system. Digital twin technology faces the challenge of completing the collection of various data on workers without putting physical and psychological pressure on them, as well as avoiding infringement on their personal privacy.

B. HUMAN-ROBOT COLLABORATION

Human-robot collaborative systems can still be more efficient. Existing technologies have limitations in human behavior prediction, cognitive assistance, and intelligent teaching, factors such as workers' age, gender, and learning ability still have an impact on the efficiency of human-machine collaboration [165]. The resulting high degree of personalization and customization needs have not yet been met, making efficient and accurate human-robot interaction and collaboration challenging. In the context of human-robot collaborative decision-making, the decision-making model is challenged by the multi-source uncertainty caused by the real-time intersection of large amounts of data [166]. Whether existing models can cope with the high uncertainty, complexity, and variability of the environment in actual production and make quick and correct decisions to ensure the efficiency and safety of human-robot collaboration, and at the same time ensure the effective integration and compatibility of various technologies in the human-machine collaboration system, and have a certain degree of flexibility and scalability, remains a problem that needs to be investigated.

In addition, human trust in robots is required for effective and high-quality human-robot collaboration. To this end, humans frequently rely on artificial intelligence systems to provide explanations for their decisions and decision-making processes. Only when these explanations are consistent with human rational thinking will humans be able to trust intelligent systems. However, existing intelligent systems based on deep learning have difficulty meeting such requirements [167], the lack of transparency, fairness and risk aversion of deep learning algorithms are still issues that cannot be ignored [168]. At the same time, the collection of workers' personal data is inevitable during human-machine collaboration. The privacy and ethical issues brought about by this data, as well as the possible risks of leakage or abuse, are all challenges currently faced. As a result, human-robot collaboration systems' explainability to human decisions requires further improvement. At the same time, humans should be able to be informed and make independent decisions about the information that is collected about them and how it is used.

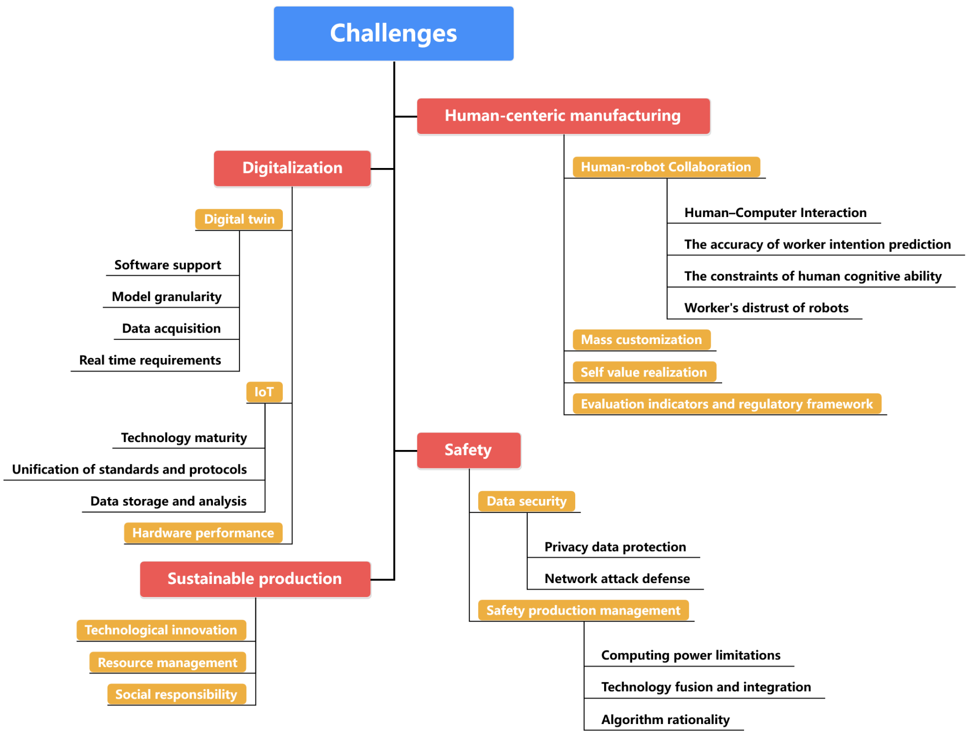


FIGURE 7. The existing challenges of intelligent manufacturing from the perspective of industry 5.0.

C. DATA SECURITY

Data security remains an urgent issue to be addressed in Industry 5.0. Industry 5.0's large-scale cyber-physical systems are often vulnerable to cyber-attacks due to their multi-attribute and heterogeneous characteristics, as well as their reliance on private and sensitive data. When a large amount of production data and user privacy information is leaked, it will cause serious consequences. Blockchain technology research needs to be improved in order to improve decentralization and protect data security. Therefore, it is crucial to explore more effective data protection solutions.

V. DEVELOPMENT OUTLOOK

A. DEVELOPMENT ROADMAP

In terms of sustainability, Ghobakhloo et al. proposed three development paths: sustainable development driven by Industry 5.0 [32], sustainable industrial transformation [169], and sustainable manufacturing [170]. The sustainable development roadmap outlines an action plan for leveraging Industry 5.0 functions to generate sustainable development value, revealing the internal promotion effect of sustainability functions. The sustainable industrial transformation roadmap describes the direct relationship between the driving factors of industrial transformation, and it believes that active government support is the most powerful driver. While the sustainable manufacturing roadmap recognizes the role of Industry 5.0 sustainable manufacturing functions as a driving force, autonomy or dependence, and the order in which they should be used, it believes that value network integration is the most fundamental driving force for sustainable manufacturing in Industry 5.0. The three roadmaps provide a reference for the sustainable application of Industry 5.0.

In terms of human orientation, Chaabi [171] returned workers to the production process by combining ADKAR and quality circles, fostering workers' trust in digital tools and alleviating the technological anxiety caused by Industry 4.0. Pizoń and Gola [172] proposed three stages for human-robot relations: safety, society, and technology. They believed that true collaboration can only occur when people trust machines.

B. FUTURE TECHNOLOGY

According to the preceding literature review, 6G communication networks have significant application potential in the fields of Internet of Things, digital twins, and human-robot collaboration. Their high data rate, large bandwidth, and ultra-low latency can not only effectively handle simultaneous access to a large number of applications while maintaining quality of experience, but also allow blockchain deployment solutions to unleash their full performance [173]. They provide significant benefits in terms of information security, operating cost reduction, and ensuring the integrity of remote resources. As a result, 6G networks are expected to play a critical role in enabling Industry 5.0.

Brain-Computer Interface (BCI) technology, as an efficient means of human-robot communication, can significantly shorten the interaction time between the operator and the collaborative robot while also improving the tacit understanding of cooperation; it can also be used in conjunction with augmented reality equipment to allow technicians to interact with the robot. Effective collaborative solutions [174] have great promise for the complex human-robot collaborative assembly required by Industry 5.0. However, wearing additional BCI devices usually interferes with workers at work, causing users to be dissatisfied with the technology. Invasive BCIs are usually accompanied by physiological and neurological side effects, and non-invasive devices whose signal quality still leaves much to be desired [175]. In addition, BCI devices may also affect workers' emotions, thinking, memory, etc., which would pose huge ethical challenges and raise doubts about the reliability of brain computer interface technology among workers. Therefore, the use of such technology may need to consider the physical and psychological burden it places on workers, as well as the resulting resistance.

Mixed Reality (MR) technology is more user-friendly and reliable than Virtual Reality (VR) technology [176], and it has a wide range of applications in operator training and skill improvement, which aligns with the Industry 5.0 paradigm's emphasis on preventing the elimination of skilled labor. In addition, MR technology can be used by operators to teach and plan paths for collaborative robots, unleashing human creativity while lowering the learning threshold and safety risks. Therefore, this article believes that MR technology will increasingly be used as an auxiliary technology for complex human-robot collaboration.

VI. CONCLUSION

This paper discusses the background and related theories that led to the birth of Industry 5.0, investigates the application scenarios of intelligent manufacturing from the perspective of Industry 5.0, summarizes the application status of existing technologies and the challenges they face, and anticipates Industry 5.0's future development. Specifically, this paper examines existing technologies and their applications of intelligent manufacturing in various scenarios, such as life cycle management, production process management, and manufacturing intelligence from the four Industry 5.0 perspectives of digitalization, human-centricity, resilience, and sustainability. This paper analyzes the technologies that may be used in the future, taking into account existing deficiencies and development paths. This paper believes that the application of Industry 5.0 technology will effectively improve the production capacity of intelligent manufacturing systems and promote the development of intelligent manufacturing systems in a safe, efficient, sustainable and resilient direction. In addition, unlike Industry 4.0, the development of Industry 5.0 will focus on the core concept of maximizing human creativity, avoiding repetitive work through human-machine collaboration, thereby improving the human-machine relationship and realizing human value.

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