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Industry 5.0: Prospect and retrospect

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ABSTRACT

Industry 5.0 blows the whistle on global industrial transformation. It aims to place humans' well-being at the center of manufacturing systems, thereby achieving social goals beyond employment and growth to provide prosperity robustly for the sustainable development of all humanity. However, the current exploration of Industry 5.0 is still in its infancy where research findings are relatively scarce and little systematic. This paper first reviews the evolutionary vein of Industry 5.0 and three leading characteristics of Industry 5.0: human-centricity, sustainability, and resiliency. The connotation system of Industry 5.0 is discussed, and its diversified essence is analyzed. Then, this paper constructs a tri-dimension system architecture for implementing Industry 5.0, namely, the technical dimension, reality dimension, and application dimension. The paper further discusses key enablers, the future implementation path, potential applications, and challenges of realistic scenarios of Industry 5.0. Finally, the limitations of the current research are discussed with potential future research directions highlighted. It is expected that this review work will arouse lively discussions and debates, and bring together the strengths of all beings for building a comprehensive system of Industry 5.0.

1. Introduction

When science replaced ignorance, capital rushed forward wrapped in a torrent of industrial steel, engulfing all conceptual innovations and technological inventions along the way, setting off a "revolutionary wave of industrialization" in England in the 1860 s. The ensuing industrial process of more than 200 years has seen mankind go through several industrial revolutions at a rapid pace. Fig. 1 shows the evolutionary history of Industry X.0. Industry 1.0 leads mankind into the "Steam Age" by using water steam to drive manufacturing equipment. As the market (one of the necessities of the Industrial Revolution) is detonated, mankind gains early material and the primitive accumulation of the economy, which leads to social change. Industry 2.0 leads mankind into the "Electric Age" by using energy as an intermediary to drive electricity. The division of labor in production throughout the whole society is clear, and the prelude to the mass-production assembly line model is opened. Industry 3.0 enables mass customization at the information technology (IT) level, while Industry 4.0 merges IT and Operational Technology (OT) in a cyber-physical system manner for mass customization/personalization with intelligence. Industry 5.0 [1,2] combines human subjectivity and intelligence with the efficiency, artificial intelligence, and precision of machines in industrial production, reflecting the value of humanistic care, thus realizing the evolution toward the symbiotic ecosystem.

The evolution of the industrial revolution has driven transformative developments in all subsystems of society. However, with the introduction of new social development concepts such as sustainability, human-centricity, and carbon emissions, the manufacturing system/paradigm has struggled to adapt to the demands of an innovative society. Industry 5.0, with its refreshing vision, will help solve the problem of the mismatch between manufacturing and social needs. Compared with past industrial revolutions that emphasized more on the economic

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aspect of sustainability, the Industry 5.0 vision leans toward human centricity and societal needs. Since the publication of the EU white paper drives toward the era of Industry 5.0 [1,2], the research trend on Industry 5.0 has been growing. However, current exploration of Industry 5.0 [1,2] is still at its initial stage, and research findings are relatively scarce and less systematic. Also, Industry 5.0-related industrial and social concepts are diverse. A systematic introduction to Industry 5.0 is absent. Motivated by this observation, this paper tries to reveal the evolutionary vein of Industry 5.0 and summarize the connotation, architecture, enabling technologies, and challenges of Industry 5.0. Thereby, relevant literature on Industry 5.0 is searched in the Web of Science database, and the retrieved papers are further refined through three processes.

Firstly, keywords of related concepts and enabling technologies are identified, including.

- Industry 5.0,
- Industry 4.0,
- Society 5.0,
- Operator 5.0,
- human-centric,
- human-robot collaboration,
- and resilient manufacturing,

to search for literature retrieval. This inclusive search yielded 3885 publications for further analysis (up to 30-June-2022). Secondly, retrieved papers are further refined based on the following criteria:

- Papers outlining the evolutionary trends between Industry 4.0 and Industry 5.0 are selected. These studies portray the current problems in the revolution and society, as well as the hopes for the fifth industrial revolution;
- papers that focus on the concepts and characteristics of Industry 5.0. These studies help to deepen the comprehension of Industry 5.0 from various perspectives;
- and papers that talk about the enabling technology and application of Industry 5.0.

Gaining insights from these studies can clarify the key enabling technology system for value-driven Industry 5.0 and the potential application directions/paths. The streamlining criteria exclude.

- studies that are not related to Industry 5.0-related concepts, technologies, or applications,
- collected papers of low quality,
- and papers not in English or less than two pages.

Finally, based on the above theoretical screening process, this paper preferentially selects the papers that mention the connotation and architecture of Industry 5.0 and eliminates the papers that describe Industry 5.0 with less space and vague viewpoints, thereby identifying the connotation system and tri-dimension architecture of Industry 5.0. 144 references are finally identified to elaborate Industry 5.0 [3]. Additionally, 26 supplementary references were added to make the review concrete, which added themes include Bionics, Symbiosis, Metaverse, Extended Reality, Heterogeneity, Mutual-cognitive, Collaborative intelligence, and Cognitive/Decentralized computing. Therefore, this review consists of 170 articles in total. Briefly, the contributions of this review work can be summarized as follows:

- **Refinement of Industry 5.0 connotation from different perspectives:** By summarizing existing important concepts related to Industry 5.0, this paper tries to reveal the evolutionary vein toward value-driven Industry 5.0. By Comparing the EU's original definition of the concepts and characteristics of Industry 5.0 with other arguments from different perspectives, this paper redefines the concept of Industry 5.0 and then summarizes its connotation, trying to help bring together the opinions from different perspectives to deepen the understanding of Industry 5.0 diversification.
- **Design of an architecture based on key enabling technologies of Industry 5.0:** This paper constructs a tri-dimension architecture of Industry 5.0, specifying the key enabling technologies, future implementation paths, and potential application scenarios of Industry 5.0. This work takes a key step toward building a comprehensive system for Industry 5.0.
- **Identification of challenges and outlook towards Industry 5.0:** Industry 5.0 as the next-generation industrial revolution will move forward in a meandering manner, inevitably encountering various limitations and challenges along the way. This paper summarizes the limitations, barriers, and challenges that may be encountered in this industrial transformation, and finally provides valuable research directions for future development.

The rest of this work is outlined as follows. Section 2 reviews the evolution from Industry 4.0 to Industry 5.0. In Section 3, the connotation system of Industry 5.0 is established. In Section 4, this paper constructs the tri-dimensional architecture of Industry 5.0. Section 5 illustrates the limitations, barriers, and challenges of the current Industry 5.0 research. In Section 6, the deficiencies of this paper and reveals valuable directions are highlighted for further exploration in the future. In Section 7, the paper concludes with a synthesis of all the above discussions.

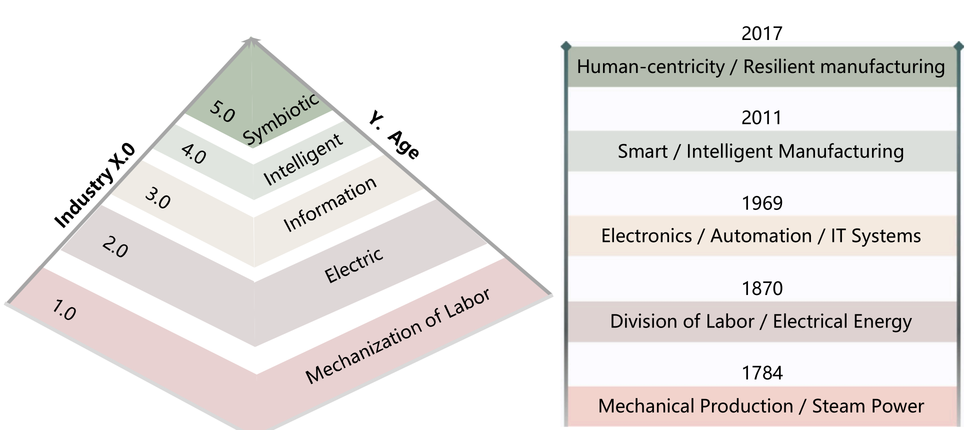

Fig. 1. The evolutionary history of Industry X.0.

2. The evolution towards Industry 5.0

The emergence of Industry 5.0 is driven by the positive impacts, and the limitations of related concepts including Industry 4.0, Society 5.0, and Operator 5.0, which are the main discussion points of the following paragraphs.

2.1. Industry 4.0

The rapid development of new-generation IT is permeating the Industry 4.0 blueprint [4]. As shown in Table 1, this paper summarized 13 typical studies [4-16] on Industry 4.0 to make an overview of the research status. Industry 4.0 is characterized by technological advancements that of substantial positive impacts on profit while neglecting the environmental and social metrics [5]. Fast industrialization also results in the degradation of the health and safety of the workers. This requires a sustainable Industry 4.0 framework [6]. Complex precedence and coupling relationships exist among different sustainability goals of Industry 4.0 [7].

On the other hand, circular economy and sustainable business models are also research trends in Industry 4.0 implementations [8,9]. Strategic, operational, environmental, and social opportunities are drivers of Industry 4.0 implementations, whereas the perception of Industry 4.0-related potentials and challenges as antecedents to Industry 4.0 implementations depends on different industry and manufacturer characteristics [10].

2.2. Operator 5.0

The rapid advances of smart sensors and wearable devices stimulate the forming of a smart operator workspace, which was identified as the Operator 4.0 paradigm [17]. The Operator 4.0 vision enables future workers to handle manufacturing complexity by complementing and enhancing their capabilities and skills instead of replacing them [18]. In the concept of Human-Cyber-Physical systems (HCPS) and adaptive automation, Operator 4.0 excels in the tasks of utilizing an automation-aided system toward a human-automation symbiosis system for a socially sustainable workforce in the human-centric smart factory [19].

Further, the Resilient Operator 5.0 is envisioned, which is divided into two parts: a) it focuses on building “self-resiliency” for the workforce because of its inherent fragility, and b) it focuses on “system-resiliency” for all human-machine systems in a manufacturing system where human operators and machines work together to ensure the optimal operation of the system [20]:

- Self-resiliency is concerned with the biological, physical, cognitive, and psychological occupational health and safety of each shop floor employee as well as their productivity.
- System resiliency considers alternative methods for maintaining the functionality of human-machine systems, such as sharing and trading control between humans and machines.

Therefore, the Fifth Industrial Revolution, or Industry 5.0, reintroduce human technicians to factory floors to increase process efficiency. This integration will combine the creativity and brainpower of humans and machines. While Industry 4.0’s primary concern is automation, Industry 5.0 will involve human and autonomous machine cooperation. The autonomous workforce will be able to detect and understand human intention and desire. Knowing that their robotic coworkers completely understand them and are capable of productively collaborating with them, humans will work alongside robots without fear. The outcomes of this fruitful collaboration will be a highly effective manufacturing process with added value, thriving trusted autonomy, and decreased waste and expenses. The next industrial revolution will usher in the so-called cobots, the next generation of robots, that either already know how to do something or can pick it up quickly, giving robotic productions a human touch. These cooperative robots will make sure that safety and risk requirements are met because they will be aware of the presence of humans. They can perceive, comprehend, and feel not only a human being but also the objectives and expectations of a human operator. Like apprentices, cobots will watch and pick up on a person’s technique. The cobots will perform the tasks once they have learned how to do so just like human operators would. All participants in this revolution should be

Table 1
Summary of the research focus of Industry 4.0.

Ref.	Technical challenges/barriers	Model / Methodology	Applications / Use cases	Enabling technologies	Research directions / Vision	Summary
[9]	H	M	L	L	L	Focused on Industry 4.0 barriers in the manufacturing sector
[11]	H	L	M	L	L	Focused on Industry 4.0 technical challenges for supply chain sustainability
[5, 7, 12]	L	H	M	L	L	Focused on sustainable development for Industry 4.0
[13]	M	L	L	H	M	Focused on new enabling technologies for Industry 4.0
[8]	L	M	H	L	M	Focused on sustainable development and key research areas for industry 4.0
[14]	L	M	L	M	L	Focused on Industry 4.0 technologies for sustainable manufacturing
[4]	L	H	M	L	L	Focused on smart manufacturing systems for Industry 4.0
[6]	L	H	L	M	M	Focused on a sustainable framework for Industry 4.0
[15]	L	M	M	L	L	Focused on Industry 4.0 technologies for industrial performance
[16]	L	M	L	M	L	Focused on a strategic roadmap toward Industry 4.0
[10]	M	H	H	L	L	Focused on what Drives the implementation of Industry 4.0

Notes: L→Low coverage, M→Medium coverage, H→High coverage.
Notes: L→Low coverage, M→Medium coverage, H→High coverage.

aware of the irreversible development trend and recognize the critical time window for effectively adapting to the new situation [21].

2.3. Society 5.0

Industry is one integral component of society. From a socio-technical system viewpoint, the transformation of the industry will promote the evolution of society, and vice versa [22]. Society 5.0 [23] was defined as "*through the high degree of merging between cyberspace and physical space, will be able to balance economic advancement with the resolution of social problems by providing goods and services that granularly address manifold latent needs regardless of locale, age, sex, or language.*" Society 5.0 envisions revolutionizing not only the industry via IT integration but also the living spaces and habits of humans. The Society 5.0 vision is characterized by four parallel concepts, namely, "a human-centric society," "merging cyberspace with physical space," "a knowledge-intensive society" and "a data-driven society", as shown in Fig. 2.

2.3.1. Toward a human-centric society

Humans must remain key players in the policy-making and decision-making processes in a harmonious society [24]. Society 5.0 vision reframes the socio-technical relationship, as well as the technology-mediated individual-society interactions [23]. To evolve toward a collaborative ecosystem of greater human security and well-being [25], it needs to employ the qualitative phenomenological anthropological and posthumanism anthropological approach to investigate the presumed human-centeredness of Society 5.0, as well as the bewilderingly diverse array of human and non-human entities, compared to earlier societies. Thus, a deeper understanding of the theoretical underpinnings and real-world implications of human future meaning can be actively promoted [26]. Society 5.0 will become a human-centric society, leading to achieving sustainable development goals (SDGs). It is also identified as one objective of the UN 2030 Agenda for Sustainable Development in 2015 [27]. A composite metric named S5I (Society 5.0 Index) to rank each country's level [28] was designed to help to understand Society 5.0 in various areas of society [27]. Under this circumstance, to obtain the super-intelligent society goal, humans are redirecting non-human entities to advance the era of a sociotechnical collaborative ecosystem [29].

2.3.2. Merging cyberspace with physical space

Merging cyberspace with physical space (which could also be identified as Metaverse) is the prerequisite of Society 5.0. In the process of merging, this cycle, whereby society is in a state of continuous adjustment and improvement, is what Society 5.0 is all about. Society 5.0 implies a much broader cyber-physical convergence and iterative improvement at the level of society as a whole. In this process, Artificial Intelligence (AI) innovations can create value in coordinating product and manufacturing services in cyberspace, which are formerly processed separately [23]. Given the impact of the covid-19 pandemic, it is critical to experiment with cross-border technological cooperation approaches through the fusion of cyberspace and physical space, leading to a sustainable, safe, and shared future [30].

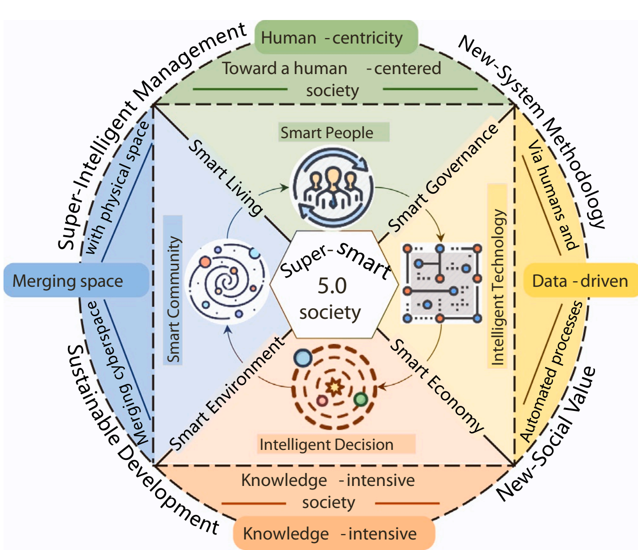

Fig. 2. The concept of Society 5.0.

2.3.3. Knowledge-intensive society

Transition from a push-based Science, Technology, and Innovation (STI) ecosystem to a pull-based STI ecosystem and enhancing the system resiliency is fundamental to revitalizing productivity in Society 5.0 [31], in which vast accumulated and shared knowledge can spark social innovation across industries [23]. Even with a large gap between AI training and real-world operations, innovative applications of human-centric management systems still could be developed to support the configuration and scheduling of processes, and human-robot cyberspace could be created for smart infrastructure design. These two new approaches can guide the selection of next-generation smart manufacturing systems [32,33]. As we move towards a truly human-centric life, we need to tap into collective intelligence [34], so that society should be prepared to make tough decisions as many societal bifurcation points are imminent [24].

2.3.4. Data-driven society

Data drives Society 5.0 in two manners. First, data drives society indirectly via people. Data inform and support human decision-making, which, in turn, affects change in society and benefits society on the road to Society 5.0. For example, smarter open government data are identified as an important driver for achieving a sustainable economy [23,35]. Second, data drive society directly (without human mediations) through dedicated designed automated processes and systems [23]. For example, an automated picking system based on the Artificial Internet of Things (AIoT) can provide speed and convenience by combining e-commerce platforms with consumer-compliant AIoT systems and robots to develop services for online stores and automated shipping systems [36]. Making evidence-based decisions through the use of AI will help solve social problems and promote innovations [24]. A data-driven society working together in the ways described above will support human-centric Society 5.0 and empower resiliency to ensure that the underlying architecture works under different disruptions and disturbances [23].

2.4. From Industry 4.0, Operator 5.0, and Society 5.0 to Industry 5.0

In the past decade, the initial blueprint of Industry 4.0 has experienced tremendous evolutions [37]. Advanced technologies, such as AI, robotics, blockchain, augmented reality, and data analytics emerge as the enablers to improve efficiency in production operations [38]. A large number of technological smart manufacturing innovations have been introduced into practice [39]. It has been speculated that by the year 2050, technology will have progressed to the point of complete autonomy [40]. The technologies brought about by Industry 4.0 have improved productivity and product quality [27], which has a positive impact on the infrastructure of society and industrialization [29]. However, unlike the technological innovation of Industry 4.0, Society 5.0, envisioned as a sustainable, inclusive socio-economic system, leads far beyond Industry 4.0 [41]. Society 5.0 incorporates the innovations of manufacturing-centered Industry 4.0 (e.g., IoT, AI, robots) [42] into both industry and social life, making mankind more conformable [43]. Society 5.0 goes beyond manufacturing and solves social problems by merging cyberspace with physical space [44] and unfolds the full potential of either human beings or the Internet [45].

Some sustainable Industry 4.0 proposals are transforming toward Society 5.0 [46]. Sustainable manufacturing systems stimulated by

Industry 4.0 is beneficial for Society 5.0, which views human as the source of innovation and technological transformation [47]. Similar to industry 4.0 which carries out the digital transformation in industries, Society 5.0 encourages humans to leap toward a digital revamp expanding across communities. The interplay and collaboration of the two prove to be a constant support for each other [48]. To guide the transition, different insights into the evolution of Society 5.0 are obtained through algorithmic co-occurrence of keywords [49], and open innovation and value co-creation are of great significance [50]. Currently, there is an urgent need to reconsider SDGs [51] and the essential role of humans in the industry's development [52]. By comparing the interrelationships between digitalization goals and SDGs reflected in the blueprints of Industry 4.0 and Society 5.0, the basis for an integrated approach that combines key provisions of the concepts of business competitiveness, sustainable development, and the information society can be found [53]. Generally, the revolutions of industry and society will complement and co-evolve in contrasting reflections.

To facilitate the elaboration of Industry 5.0 transformation, related concepts including Industry 4.0, Society 5.0, and Operator 5.0 could be summarized into a unified system, namely "Industry 4.1″ [1], as shown in Fig. 3, which has been mentioned in the EU white paper [1]. A new industrial revolution is bound to take a long time, so it is necessary to establish a buffer period between Industry 4.0 and Industry 5.0. The human-centric super-smart society, Society 5.0, is well suited to this role and lays the social foundation for the transition to Industry 5.0. In addition, Operator 5.0 provides a reference point for the smart manufacturing paradigm of Human-Robot Collaboration (HRC), reflecting the importance of human-centric thinking. The concept of Industry 5.0 is certainly advanced, it represents a starting point. However, the emergence of Industry 5.0 is not accidental, but a necessity in the process of industrial history when the world's industrial level develops to a certain period and people's living standards develop to a certain stage.

It could be concluded that many concepts in Fig. 3 are in line with Industry 5.0. In the evolution toward Industry 5.0, Industry 4.0 lays the technical foundation, and Society 5.0 focuses the societal needs, while Operator 5.0 emphasis on the human aspect. Industry 5.0 is neither a replacement nor an alternative, but evolution and logical continuation of the existing Industry 4.1. After gaining a clearer understanding of the development lineage for Industry 4.1 through the evaluation of the current research status of Industry 4.0, Society 5.0, and Operator 5.0, this paper further discusses the connotation of Industry 5.0.

3. Connotation of Industry 5.0

Current research mainly focuses on concept interpretation, feature analysis, and HRC on Industry 5.0. The scope of research is mostly limited to either the definition of Industry 5.0 provided by the EU or the expansion of the manufacturing paradigm of mass individualization. At the same time, Industry 5.0 is also considered the "Sublation" of Industry 4.0 and is still in the preliminary exploration stage. As a result, there is a lack of systematic research results and a lack of authoritative literature. After summarizing the research status and achievements, this section discusses the connotation of Industry 5.0. A conceptual framework of the connotation system of Industry 5.0 is proposed as shown in Fig. 4. We can not forget that Smart Manufacturing and Industry 4.0 was always defined specifically including human ingenuity as a key enabler.

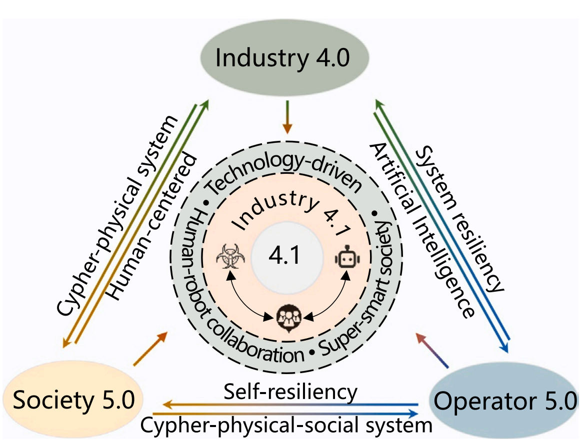

Fig. 3. A unified "Industry 4.1″ [1] system comprised of Industry 4.0, Operator 5.0, and Society 5.0.

3.1. *Definition of Industry 5.0*

The starting point of the Industry 5.0 revolution stems from the change in the relationship between humans and intelligent systems. To figure out what exactly Industry 5.0 is and what value it will bring, Table 2 provides an overview of the definition of Industry 5.0 from three perspectives. The first definition is derived from the research work of Breque et al. [2], who realize Industry 5.0 is a thoughtful concept considering the future of the industry as a manufacturing/production system that is human-centric, sustainable, and resilient. Another definition is provided by Nahavandi [54], stating that within a factory, human workforce and machines work together in close collaboration in order to increase process efficiency by utilizing human creativity and brainpower through the integration of workflows with intelligent systems. Accordingly, Friedman and Hendry [55] defined that Industry 5.0 is expected to force business professionals, information technologists, and philosophers to concentrate on human factors when implementing new technologies in industrial systems. Consequently, Industry 5.0 can be considered as the era of the socially intelligent factory, in which cobots converse with people. Enterprise social networks will be used by Social Smart Factory for enabling seamless communication between human and CPPS components [56]. The overall current understanding of Industry 5.0 brings the human touch back to the industry. It also entails the incorporation of AI into human operations to enhance man's capacity. The core of Industry 5.0 is the harmony of machines, humans, values, tasks, and finally, knowledge and skills which results in personalized/individualized products as well as services.

Considering the definitions provided above, it becomes apparent that all of them converge in the aspects of human-centricity, system resiliency, sustainability, and collaborative intelligence. However, further interpretation of the definitions can highlight key differences. Albeit the majority of the Industry 5.0 definitions entails an entire technological and societal era, the rest of the definitions focus more on industrial transformation.

Industry 5.0 is an open and evolving concept that moving toward a collaborative and co-creative vision of the World Industrial System of the future. Nonetheless, the paper believes the core of Industry 5.0 can be defined as follows: *Industry 5.0 places the well-being of the workers at the center of the manufacturing process by making production respect the boundaries of our planet and the harmonious symbiosis between humans and machines, to achieve societal goals beyond jobs and economic growth, and further achieve sustainable development goal of super-smart society and ecological values, which will become a robust and resilient provider of prosperity in an Industrial Community of Shared Future.*

3.2. *Characteristics of Industry 5.0*

The White Paper on Industry 5.0 released by the EU mentioned that Industry 5.0 has three characteristics: human-centricity, sustainability, and resiliency. However, either Industry 5.0 or Industry 4.0 has different degrees of concept improvement in revolutionizing the way industries operate [63].

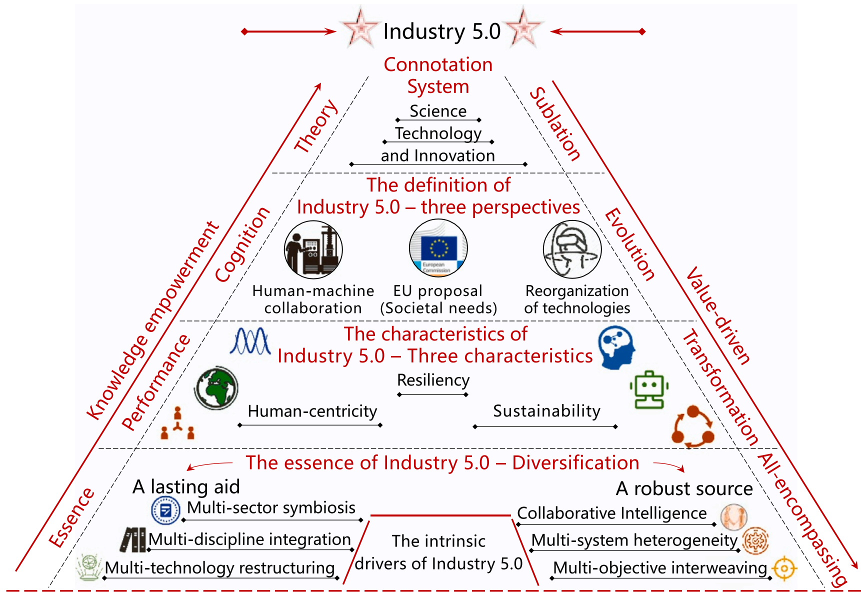

Fig. 4. The connotation system of Industry 5.0.

3.2.1. *Human-centricity*

Under the mass individualization demands from prosumers, humans cannot be replaced by machines or robots in the industry [64,65]. No automation or digitalization could be achieved without humans [65,66]. The reason is that human presence brings the system more fault tolerance capabilities [67]. Industry 5.0 sets the worker pillar in the center of the production systems [68]. Human-centric manufacturing is a prerequisite for factories pursuing flexibility, agility, and robustness against disruptions [69–71]. Synergistically combining human and robot abilities avoid cumbersome operations and improve workers' health and safety conditions [72,73]. Human-centricity goes beyond the conventional human factors and treats human needs and interests as the core of the manufacturing process, shifting from a technology-driven approach to a thoroughly human-centric and society-centric one [74].

Human-centricity should not be a one-way road. Otherwise, technologies will not unfold their full potential [2]. Utilize a human-centric AI thinking approach to analyze key socio-environmental data for AI-enhanced decision support to inform global sustainable development [75]. Introducing human-centric thinking into industrial work systems is a viable solution to overcome existing barriers, which improve overall system performance and human well-being. At the same time, human factors and ergonomics are combined to meet the challenges of social technology. Human-centricity calls for Intelligent robots capable of understanding the increasingly coupled relationships between humans and machines in unstructured environments [76], in which Human-Centric Explainable AI (HC-XAI) is the foundation [77]. In a broader human-centric society, the bonds of trust are unbreakable, and everyone can work peacefully by autonomously ensuring the security and stability of communication networks that serve as social infrastructure [23].

3.2.2. *Sustainability*

All past industry revolutions present a unanimous acceptance of the greater benefits of being sustainable [78]. Sustainable manufacturing is critical for the sustainable development of society in aspects such as renewable energy sources [79]. Sustainable manufacturing is a blueprint in United Nations' SDGs, in the "Responsible consumption and production" and "Industry, innovation, and infrastructure" aspects. Sustainability is hinged on the innovation of products and services [80]. For delivering mass-individualized products and services [81], a sustainable manufacturing vision lies in the new feature of the decentralized interconnection of socialized manufacturing resources and open architectural products [79]. Furthermore, customers anticipate product providers to provide product information on social sustainability, but providers usually lack traceability in their multi-tier supply chains (in which blockchain is a solution) [79,82].

Sustainability considers three pillars economy, environment, and society. Compared with past industrial revolutions, the current Industry 5.0 visions lean toward human centricity and society needs, making the three pillars of sustainability unbalanced, whereas it should be a balanced solution. The economic aspect of sustainability is still supposed to be important in the reorganization of technologies in realizing the Industry 5.0 vision. Sustainable implementation of Industry 5.0 is to adjust the position of one factor in the three pillars at the right time in different stages, to better achieve the global construction of Industry 5.0 with more quantity, faster speed, better quality, and cost savings.

3.2.3. *Resiliency*

Resiliency refers to the ability of a system to keep or recover quickly to a stable state, during and after a major mishap caused by (geo-)political shifts and natural emergencies such as the COVID-19 pandemic, or in the presence of continuous significant stresses [83]. Achieving a high level of resiliency is a recognized essential ability of Industry 5.0 [84]. Because Industry 5.0 not only pays attention to the ability of enterprises to deal with external uncertainties, such as the uncertainty of markets, supply chains, and customers, but also pays attention to the resiliency of a wider range of industrial systems, such as the entire industrial chain, and even the industrial system of a country or region to unknown risks [85].

3.3. *Essence of Industry 5.0*

The definition and characteristics of Industry 5.0 specify the evolutionary vision of the industry, while the essence of Industry 5.0 refines the intrinsic composition of Industry 5.0 and exposes the intrinsic drivers of Industry 5.0, which are fundamental to its eventual realization. In short, it will be an all-encompassing human-centric expansion, a lasting aid to sustainability, and a robust source of resiliency.

3.3.1. *Collaborative intelligence*

Collaborative Intelligence is defined as the joining forces of Humans and artificial intelligence [86]. In Industry 5.0 context, collaborative

Table 2
Definitions of Industry 5.0.

Perspectives	Ref.	Definitions
EU proposal-based	[2]	Recognize 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 of our planet and placing the wellbeing of the industry worker at the center of the production process.
	[57]	A manufacturing paradigm places a premium on worker well-being throughout the manufacturing process and leverages new technologies to create wealth beyond employment and development, all while keeping conscious of the planet's production restrictions.
	[58]	Recognizes the power of industry to become a resilient provider of prosperity, by having a high degree of robustness, focusing on sustainable production, and placing the well-being of industry workers at the center of the production process.
Human-machine collaboration-based	[54]	Human workforce and machines work together in close collaboration in order to increase process efficiency by utilizing human creativity and brainpower.
	[59]	Humans will be able to rejoin the automated process and cooperate with a new generation of Cobots to add value to products.
	[54]	A synergy between humans and autonomous machines. The autonomous workforce will be perceptive and informed about human intention and desire.
	[60]	A human-centric design solution where the ideal human companion and Cobots collaborate with human resources to enable personalizable autonomous manufacturing through enterprise social networks.
	[61]	An 'Age of Augmentation' when the human and machine reconcile and work in perfect symbiosis with one another.
Intelligent cutting-edge technology-based	[55]	Force business professionals, information technologists, and philosophers to concentrate on human factors when implementing new technologies in industrial systems
	[62]	A new business concept using an intelligent manufacturing system with the use of intelligent devices. It will meet & exceed the requirements of customer delight, personalization, improved productivity, efficiency, and quality of the product.

intelligence implies the ability of mutual-cognitive coordination between human intelligence and artificial intelligence in machines to co-innovate, co-design, and co-create individualized products and services. Through such collaborative intelligence, humans and artificial intelligence in machines actively enhance each other's complementary strengths: the intuition, leadership, teamwork, creativity, versatile problem-solving, and social skills of workers, and the speed, scalability, endurance, and quantitative accuracy capabilities of machines. The Industry 5.0 research and practices are supposed to figure out how workers can effectively augment machines, and how machines can enhance what workers reach their full potential. In the former scene, workers need to play three roles in augmenting machines, namely, 1) training machines to fulfill specific tasks; 2) explaining counterintuitive or controversial outcomes of those tasks; and 3) sustaining the responsible use of machines. In the later scene, machines need to help workers expand their potential in three aspects, namely, 1) amplifying workers' cognitive abilities; 2) interacting with customers and employees to free workers from low-level tasks; and 3) embodying workers' skills to extend their physical capabilities [86].

3.3.2. *Multi-objective interweaving*

Industry 5.0 will have diversified goals including human efficiency, productivity, and customers' individualized requirements in many fields, such as social and ecological fields [87], smart healthcare [88], and economics [44,62,89,90], which will also counteract Industry 5.0. Enterprises in different industries have continually started to implement various social responsibility projects and sustainable manufacturing programs. The future will welcome a transition from a flexible modularized system to an autonomous learning system, which self-programs, self-organizes, and self-optimizes to form a human-centered manufacturing system for Industry 5.0.

To sum up, through the multi-objective interweaving, Industry 5.0 will also be actively promoted, leading the economic recovery and industrial transformation of various industries, and its significance in the comprehensive context of global energy conservation and emission reduction has become prominent.

3.3.3. *Multi-technology restructuring*

Industry 4.0, with its "digitalization" transformation trend, emphasizes adopting advanced technologies to remove human beings from manufacturing processes and systems [90]. Faced with the industrial status quo towards human-centric Industry 5.0, the restructuring of new-generation information technology is imminent. The restructuring of new-generation information technologies such as blockchain and HRC does not mean the simple stacking of technologies, but the timely empowerment of the demand for Industry 5.0 by using cutting-edge technologies in different advanced technologies to gradually transition from technology-driven industry 4.0 era to value-driven industry 5.0 era. Reorganized smart technologies foster the dissemination of discoveries and advance the ability of robots to collaborate with humans [76].

The reorganization of technology in Industry 4.0 will discard the part of technology application that ignores humanistic thought and pay attention to the future of human value in technological innovation. Industry 5.0 can drive the transformation of the world's industrial system, the acceleration of production processes, and the changing roles of workers. This will provide a historical opportunity for the high-end, intelligent, and green development of the global manufacturing industry, and also allow the concept of Industry 5.0 to show more possibilities for implementation.

3.3.4. *Multi-discipline integration*

Since Industry 5.0 involves the all-around evolution of the industrial system, it is necessary to adopt an interdisciplinary approach in engineering, technology, life sciences, environmental and social sciences, and humanities, and to achieve multi-disciplinary intersection while accelerating interdisciplinary integration. Different disciplines learn from each other's strengths and complement each other's weaknesses, interweaving and blending, such as an ever-changing dynamic network, to meet the needs of various complex industrial systems, and can also inject new vitality into sectors other than manufacturing and generate new value.

To this end, a new interdisciplinary engineering approach to measure and promote social sustainability on production sites can serve as a reference. To improve the workers' well-being, health, satisfaction, and performance, the redesign of manufacturing systems toward human-centric connected systems calls for multi-disciplinary intersected expertise [66].

3.3.5. *Multi-sector symbiosis*

The symbiosis of three parts: technology, society, and ecology, forms the essence of Industry 5.0. Industry 5.0 acknowledges the power of technology for industrial (commercial) revolution but combines the satisfaction of economic goals with social goals in the system (for example, emphasizing workplace safety through the use of new-generation technologies or human-robot relations) and social goals outside the workplace (social and environmental responsibilities) [44]. This multi-objective combination requires the harmonious symbiosis of the entire national sector to unfold.

In a country, the ministry of science and technology, the ministry of social and people's livelihood, the ministry of ecological management, and other ministries use empathy as a link to understand the difficulties in each other's development process; On the condition of sharing, under the condition of information and resource sharing, under the synergy of multi-sector cross-linkage, the governance capacity of the entire industrial society will be improved. Based on a virtuous circle of empathy and sharing among multiple ministries, it will drive the harmonious symbiosis of the entire country. Further, based on the symbiosis of multiple ministries, Industry 5.0 can respond to emergencies in the supply chain with high flexibility, enhance the core competitiveness of the value chain sustainably, and then stabilize the orderliness of the entire industrial chain ecosystem.

This harmonious system of multi-sector symbiosis in the country will also promote the development of industrial symbiosis. Industrial symbiosis focuses on the construction of ecological chains and ecological networks in the park, maximizes resource utilization, minimizes industrial emissions, and realizes regional clean production. Different from the conventional "design-production-use-disposal" method, the eco-industrial park follows a circular economy model of "recycling-reuse-design-production".

We can certainly believe that the action and reaction between the two will serve as an inherent and enduring driving force in the system of Industry 5.0 to achieve a deeper level of manufacturing upgrades.

3.3.6. Multi-systems heterogeneity

In the industrial field, heterogeneous devices can make it difficult to interconnect data and information because of system mismatch [91]. With the advancement of technology, a large number of emerging smart devices have emerged, which urgently requires a heterogeneous system to solve the problem of system heterogeneity among smart devices [92]. Based on the well-known CPS concept used in Industry 4.0 [93], different heterogeneous system integration concepts such as human-cyber-physical system (HCPS) and cyber-physical-social system (CPSS) had been proposed, providing a reference value for building an Industry 5.0 era.

On one hand, human roles keep evolving toward co-existence with automated manufacturing assets [94]. Experiences in which automation may confront difficulties in generating consciousness and cognitive intelligence when substituting humans. Scholars proposed HCPS that consciously seeks a harmonious approach to work with the best part of both machines and humans. [95]. HCPS is a composite intelligent system comprising humans, cyber systems, and physical systems in order to achieve sustainable goals at an optimized level [96,97]. Human systems interact and coordinate with cyber and physical systems in a shared context that is generated by ubiquitous/cognitive computing, which greatly augments human abilities [98].

On another hand, driven by the development of cognitive computing technology, social characteristics and interactions are incorporated into the CPS [99]. CPSS goes beyond the cyber-physical integration by the inclusion of social space (including crowd mental capabilities and sociocultural elements) [100]. Information from cyberspace interacts with physical and mental spaces in the real world, as well as artificial space mapping different elements and relationships of the real world [101]. On one hand, CPSS enables parallel execution and self-synchronization among the physical, information, and social domains [102]. On another hand, CPSS-based context-aware social IoT provides a potential approach for handling the boosting sociality resulting from the customers' mass individualized requirements at the manufacturing process level [103]. Through smart coordination of social entities, the efforts made in CPSS will converge for establishing a parallel society that aims to achieve an innovative social infrastructure with equal rights, and information symmetry, as well as to reshape values and service quality [104].

From CPS to HCPS and then to CPSS, it can be seen that the value of people as independent subjects in various systems is gradually highlighted. Industry 5.0 will be an important future of multi-systems heterogeneity, where humans-new machines-software-information technology is integrated to provide world-class manufacturing heterogeneous systems [105]. In the society of ternary fusion integration, everybody will become a link of innovation and resource organization toward comprehensive value-creating and development [106].

4. A tri-dimension architecture for implementing Industry 5.0

At present, there are few systematic research results on Industry 5.0. As shown in Fig. 5, this paper builds a tri-dimensional architecture of Industry 5.0 based on the technical dimension, reality dimension, and application dimension, hoping to arouse an intensive discussion on the architecture of Industry 5.0.

4.1. Enablers of Industry 5.0

Enabling technology trends such as HRS, digital twin, blockchain, big data, metaverse, and human factors engineering are combined in innovation with cognitive skills and development concepts, thus enabling the flow of advanced knowledge across technologies and enabling a value-driven Industrial 5.0 model with technological support. Based on the literature survey, typical enabling technologies and techniques for the realization of Industry 5.0 have been compiled. However, the identification of technological enablers is the first step toward Industry 5.0. Additionally, a comprehensive description of the identified enablers is summarized in Table 3.

4.1.1. Ergonomics and bionics

Ergonomics is the intersection of human ergonomics, engineering, and human-robot-environment system, aiming to study the problem of human work optimization. With humans as the driver, human science including psychology, physiology, anatomy, and anthropometry is applied to engineering design and work operations management, especially considering human work safety. The ergonomics research is of great significance in analyzing, understanding, and designing human work in Industry 5.0 [107]. Human-centric, focusing on improving human performance in the industry, preventing worker errors, and optimizing the holistic performance of the human-robot-environment

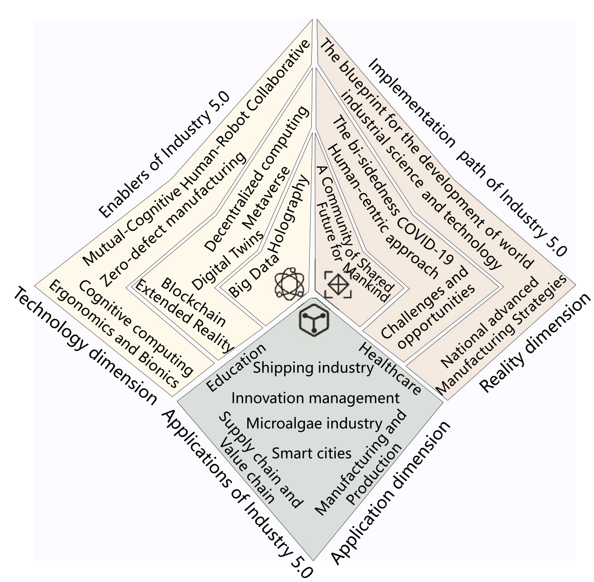

Fig. 5. A tri-dimension architecture of implementing Industry 5.0.

Table 3
Enables of Industry 5.0 and Area of Application.

Type	Enablers	Area of Application
Human-machine collaboration	Ergonomics [107]	Analyzing, understanding, and designing human work.
	Mutual-Cognitive Human-Robot Collaboration [111]	Eliminating possible faults of manual or robotic manufacturing while enhancing flexibility and reconfigurability.
	Recommender system technology [120]	Benefiting the collaboration of human beings and machines.
	Bionics [56]	Healthcare, orthopedics, medicine, surgery, and chemical industries.
Simulation capabilities	Advanced Simulation [121]	Produce more resilient, sustainable design.
	Cyber-Physical Systems (CPS) [122]	Complete industrial automation for more robustness and flexibility.
	Digital Twin [123]	Enhanced resiliency in industrial planning and simulation.
	Metaverse [124]	Bring immersion and presence to HRC.
	IoT-Enabled Systems [125]	Remote access and enhanced accessibility.
	Extended Reality (XR) [126]	Simulation, prototyping, product design, personalized education.
	Internet of Everything (IoE) [62]	Creating intelligent connections and new capabilities.
	Holography [127]	3D visualization in space, especially human visualization.
Computing infrastructures	Blockchain [128,129]	A robust and resilient mechanism for product life-cycle data management.
	Decentralized Computing [130]	Enabling autonomy and decentralization in the manufacturing system.
	Big Data [131]	Enhanced resiliency in service and more freedom of mass-personalization.
	Cognitive Computing [62,132]	Supporting decision processes for in-situ workers.
	Green Computing [133]	Bio-oriented and sustainable computing.
	AI-based Management Systems [134]	Better task allocation, better handling of reiterative jobs, better service.
Societal needs	Waste Prevention [44]	Refusal and removal of intoxicating practices, materials, and byproducts.
	Smart Materials [62]	Applicable in defense, medical, manufacturing, and automotive industry.
	Disaster mitigation [60, 135]	Enhancing system resiliency.
	Renewable Energy Sources [136]	Reducing fossil fuel emissions, and reach sustainability goal 7 (SDG 7).
	Sustainable Agricultural Production [137]	Resilient Production, Land Fertility Preservation, and Pollution Removal.
	Zero-defect Manufacturing [138]	Quality management/assurance, and sustainable production.
	Fin-tech [139]	Fast, secure, resilient digital systems, improved digital transactions.

system under the premise of enabling the system as comfortable, safe, and satisfying as possible for the workers [108].

In summary, the research objectives of ergonomics mainly focus on improving work efficiency and quality and satisfying human value needs. The research content of ergonomics focuses on the interrelationship between human beings and the products, equipment, facilities, operations, and environments in working; and the research methods systematically study information about worker capabilities, behaviors, limitations, and preferences, and use them for designing and manufacturing of products, operating procedures, and the environments in which they are used. Coping with the rapidly growing challenge of human-robot-environment integration in the Industry 5.0 blueprint [109], more attention should be paid to the technological integration of ergonomics and human-robot safety, concerning workers' well-being and psychophysical needs. And cognitive ergonomics is an underestimated topic in Industry 5.0 [110].

Bionics which extends the topic of Bioengineering will provide towards the realization of Operator 5.0. Bionics are defined as the mimicking of nature inventions. However, nature is of great interest to engineers, as there are several inventions in fields that still require further studying to fully conceive them. Briefly, the fields of Bioeconomy, White Biotechnology, and Synthetic Biology, are mentioned among others.

4.1.2. Mutual-cognitive human-robot collaboration

The research on HRC has gone through multiple periods, namely, Human-Robot Interaction (HRI), Human-Robot Collaboration (HRC), Symbiotic HRC, and Proactive HRC [111]. Recent advances in HRC research have accelerated the arrival of the era of Industry 5.0.

HRI is to augment the experience of a robot user by making robots more friendly and convenient with manifold interaction manners, such as speech recognition, eye detection, and fingerprint [112]. HRC is a 'state in which a purposely designed robot system and an operator work on simultaneous tasks within a collaborative workspace'. It implies no temporal or spatial separation of the robotic and human activities (e.g., semaphores or fences) [113]. From HRI to HRC, the difference lies in that HRC in production forms a context where workers can work side by side with robots nearby. The collaboration aims to combine the advantages of the two: strength, endurance, repeatability, and accuracy of the robots with the intuition, flexibility, and versatile problem-solving and sensory skills of workers. Human intelligence works in harmony with cognitive computing, resulting in user-centered products/services [114]. Given the human-centric and resilient vision of Industry 5.0, HRC can be implemented to improve productivity and workers' well-being, eliminating possible faults of manual or robotic manufacturing while enhancing flexibility and reconfigurability [115].

Symbiotic HRC places the interplay of humans and machines into a human-cyber-physical-interconnected system where human and robotic agents interact in a shared context to fulfill complex production tasks [116]. From HRC to Symbiotic HRC, the difference lies in that the Symbiotic HRC system possesses the skills and advantages of perception, processing, reasoning, decision making, adaptive execution, mutual support, and self-learning through real-time multimodal communication for contextual-aware HRC [116]. Taking the Symbiotic HRC one step further, the Proactive HRC [111] not only helps each other in physical behavior but also proactively understands and empathizes with each other at the cognitive level of thinking, using knowledge as a medium of communication [117]. The cognitive capability makes operators collaborate with robots more cognitively [118]. During collaborative work, humans become aware of the adaptive execution of updates for optimal productivity, while the robot can learn human intention and present better compatibility with the human in real-time collaboration [111]. Several Proactive HRC solutions have been proposed, such as a visual reasoning-based approach for Mutual-Cognitive Human-Robot Collaboration (MCHRC) [117], mutual-cognition generation in Proactive HRC systems [119], and a multimodal transfer-learning-enabled action prediction approach [111].

In the future, based on advanced AR, IIoT, cognitive computing, and robotic mechanism design, the mutual cognition for Proactive HRC can be unfolded into the full potential to assist with human-centric manufacturing. With the implementation of proactive HRC, it is foreseen that it will dominate the next-generation smart manufacturing paradigm, which will largely contribute to the construction of value-driven Industry 5.0 [111,117–119,140]. Nevertheless, existing MCHRC systems are still far from a comprehensive symbiosis of robotic and human cognitions.

4.1.3. Digital twins and metaverse

CPS has been greatly investigated under the framework of Industry 4.0. However, as discussed in the previous paragraphs, Industry 5.0 will be focused more on the improvement of humans and human operators other than on the technological improvement of systems. Therefore, new concepts, putting humans in the loop, have emerged, such as the Human Cyber-Physical Systems (HCPS). No matter what the new idea or technology is, it only makes sense when it creates value. Nowadays, the digital twin trend is gaining momentum due to rapidly advancing AI and big data analytics, as well as the availability of IoT sensors and computing infrastructure, reducing maintenance costs and improving the performance of the system. In Industry 5.0, digital twin technologies provide a potent online emulation tool for supporting the (re)design [141], (re)configuration [142], (de)commissioning [143], and optimized operating [144,145] of human-centric manufacturing systems. Rapid-response AI algorithms can be incorporated into the digital twin for performing dynamic optimization based on real-time data to enhance design quality and operational efficiency. Digital twin avoids the considerable cost of full-physical reconfiguration/commissioning if design deficiencies are found in the deployment process of the conventional irreversible virtual design approach.

With the advent of the value-driven Industry 5.0 era, the amount of data available to us in the process of interaction continues to expand, and the dimensions of data continue to overlap. By adding another dimension to the "two-dimensional picture" of the Internet, we can further avoid "information blindness". In industrial scenarios, the existence of "information blindness" means that managers are unable to control the overall situation and take timely action if problems occur at key points. This may affect the productivity of the factory, and may also cause production accidents and even casualties.

Metaverse is a potential enabling technology of Industry 5.0 to solve the problem mentioned above. As defined by Dr. Yu Yuan [124], the Chairman of IEEE Standard Association, Metaverse may refer to a kind of experience in which the outside world is perceived by the users (human or non-human) as being a universe that is built upon digital technologies as a different universe ("Virtual Reality"), a digital extension of our current universe ("Augmented Reality" or "Mixed Reality"), or a digital counterpart of our current universe ("Digital Twin"). Named after the universe, a metaverse shall be persistent and should be massive, comprehensive, immersive, and self-consistent (https://engagestandards.ieee.org/). Described as "meta", a metaverse should be ultra-realistic, accessible, pervasive, and may be decentralized. In a narrow sense, metaverse may be simply defined as Persistent Virtual Reality (PVR). In a broad sense, the metaverse is the advanced stage and long-term vision of Digital Transformation [124]. The greatest value of the metaverse is to bring immersion and presence to HRC.

There exist some examples of metaverse applications in some industrial scenarios. For instance, Metaverse in a virtual e-learning environment [146] makes it easy to develop future metaverse-based applications. Metaverse in cardiovascular medicine [147] accelerates the adoption of telemedicine in cardiovascular health and introduces a new dimension to disease education, prevention, and diagnosis. Metaverse in the environment and biodiversity [148] develops themes and content for use in the virtual world of the metaverse to ensure that biodiversity works well in the future. The metaverse may also change the way the hospitality and tourism industry operates [149]. By having customers' experience in the virtual world, service providers can collect data on changes in consumer behavior and thus improve real-world marketing and operational strategies in time with the help of debugging in the virtual world.

ICT infrastructure is the cornerstone of the success of the metaverse. Digital Twin is a digital infrastructure that exists symmetrically with the physical world in the future "Metaverse", which greatly enhances the efficiency and realism of the Metaverse. On the one hand, the metaverse as an emerging technology can provide a brand-new impetus for industrial development (the Industrial Internet can be understood as a part of the industrial metaverse). On the other hand, the core technologies in it have created a lot of value in the industrial field today. Extending to the industrial scene, we can build a mixed reality environment through virtual reality technology to simulate the production process before production to identify and solve problems in advance. Of course, it is also possible to re-simulate specific problems after production to analyze the problems and trace the causes [150].

Industry 5.0 in the era of human-centeredness is equivalent to reconstructing a meta-universe that is an exact mirror image of the real world and allows everyone to create any material and spiritual works online, so technology needs to be given a moral anchor so that it serves humans instead of harming them. Through digital empowerment, the meta-universe helps the smart manufacturing of Industry 5.0 to develop towards a human-centric, sustainable, and resilient quality.

4.1.4. Extended reality and holography

Virtual Reality and Holography can be described more efficiently by the introduction of the term Extended Reality (XR). As the name implies XR frameworks enable the projection of digital/virtual information on the users' physical environment. Consequently, with the integration of XR frameworks, the concept of the augmented operator becomes a reality. It is stressed that XR is an umbrella term that encapsulates three key technologies, in particular, i) Augmented Reality (AR), ii) Mixed Reality (MR) (which is in line with holography), and iii) Virtual Reality (VR). Holography could be used to test for any defects, breaks, and quality control to detect problems and errors in the Industry 5.0 process [62]. It could store worker data and provide detailed structures of a worker, which is more useful for the planning of complex operations.

4.1.5. Big data analytics and cognitive computing

IoT systems and Big Data are two intertwined terms. The integration of IoT in modern production, and by extension in modern society, has enabled the communication of devices that are connected between each other and with humans as well. Thus, great streams of data are being produced and communicated on a global scale. Big Data Analysis and Analytics have come to the foreground, in an attempt to fully utilize the big data sets and get valuable insights into the events they describe. With the rise of 5 G networks, the transmission of data streams has been further improved, hitting approximately Three-Fourths of a billion 5 G connections, during the first quarter (Q1) of 2022. Bigger data sets can be transmitted at faster bit rates and more reliably. However, there is a limitation that has to be seriously considered by engineers, the transmission, storage, and processing of non-valuable data. Consequently, the challenge arising here is to design and develop new frameworks as well as to further elaborate existing frameworks in order to eliminate such phenomena.

Using semantics and ontology technology to tackle the interoperability challenge [151], a cognitive computing system can collect real-time context data from real-world systems to analyze processes, and thus form insightful information and support decision processes for in-situ workers [152]. Industry 5.0 provides symmetric innovation for the digital storage of data using cognitive computing technologies [60]. Cognitive computing and big data analytics tend to be fast-changing technologies with many opportunities in Industry 5.0 implementations [153,154]. Some Industry 5.0 studies use big data analytics to better percept customers' behavior to optimize product pricing decisions and support overhead cost reduction, which contributes to quality checks and thoughtful decision-making [62,132]. In the continuous process improvement of an Industry 5.0 system, it is often necessary to collect detailed data about the whole manufacturing cycle [155]. Big data analytics techniques could be implemented to discover and eliminate non-essentialities to optimize predictability [60], which will help promote the application and optimization of big data [156]. This feature is applied in many Industry 5.0 fields, such as manufacturing, healthcare, finance, retail, and management to optimize the sustainable industrial value chain [157].

4.1.6. Blockchain and decentralized computing

Autonomy and decentralization are of great significance in enhancing the overall manufacturing system performance [158]. As mentioned before, Industry 5.0 has the characteristics of multi-sector symbiosis and multi-system heterogeneity, which brings serious challenges to the management of data and information among heterogeneous devices. Blockchain, as a secure and shareable decentralized computing paradigm [130], may provide significant added value for Industry 5.0 [60]. And its enabling aspects are diverse in Industry 5.0. Firstly, at the IoT level, blockchain could be employed to create secure digital identities for distributed workers, machines, and robots in Industry 5.0 for efficient system management [60]. Also, the blockchain may provide a secure interface for other cyber systems, which solves the authentication problem of device heterogeneity [79], as well as privacy protection of workers' information in HRC. Secondly, at the process level, blockchained smart contracts may promote automating the coordinating process by automating the agreement between different agents/ stakeholders, such as the ManuChain [159] model to get rid of inconsistency between holistic planning and local manufacturing execution. Moreover, blockchained smart contracts can be adopted for smart product service-oriented actions for resilient individualized manufacturing towards Industry 5.0 [128,129], such as the Makerchain [160] model to handle the cyber-credit of SM among various makers. The inherited transparency and traceability features of blockchain form trust through secure P2P transactions [3]. Thirdly, from the product life-cycle management perspective, it is foreseeable that in Industry 5.0, blockchain may also be actively used in the field of industrial intellectual property protection and sharing.

Blockchain is a new generation of secure information technology that promotes the construction of Industry 5.0, which can accelerate the creation of more sustainable communities, provide a robust and resilient mechanism, and use the decentralized computing model to serve the people, govern and reshape the entire human society. In the long run, blockchain-based product life-cycle data management is supposed to be able to cut down the supervision costs of Industry 5.0 [79].

4.1.7. Zero-defect manufacturing

Product quality management is also a critical aspect of evaluating the performance of a manufacturing system. Conventional quality-oriented manufacturing management methods are hardly adapted to the sustainable development of industrial systems. The technological concept of Zero Defect Manufacturing (ZDM) [138] is a potential enabler for increasing the sustainability of products and manufacturing systems in the era of Industry 5.0. Human factor in manufacturing has an impact on manufacturing quality that cannot be ignored. ZDM, combined with the human-centered thinking of Industry 5.0, is bound to optimize the overall quality of employees [161]. Product- and process-oriented ZDM could continuously improve the entire production chain by predicting when defects are likely to occur and thus preventing them, accelerating the transition of manufacturing methods from quality-oriented to value-driven Industry 5.0 [162]. The quality system based on a holistic ZDM approach is expected to become the new standard for manufacturing in Industry 5.0.

4.1.8. Other enabling technologies

[138]Besides the enabling technologies mentioned above, there exist many other basic technologies enabling Industry 5.0. To name a few, the Internet of Everything (IoE) brings humans, data, processes, and things to create intelligent connections and new capabilities in the enterprise, which could be used in Industry 5.0 [62]. Natural communication and semantic-based task-oriented dialogue technology [108] allow humans to naturally interact with machines and robots. Also, the recommender system technology [120] for industry 5.0 will benefit the collaboration of human beings and machines with more focus on customers' personalization requirements. Meantime, advances in disaster mitigation [60, 135] must be maximized for enhancing system resiliency in Industry 5.0. In Precision Agriculture as well as Sustainable Agricultural Production, there is still room for further improvement, in order to fully exploit the fields, reduce bad seeds (zero waste – Zero Defect Manufacturing), and maintain endangered species. AI will be among the greatest contributors towards this direction, as it provides engineers with advanced/sophisticated decision support tools.

4.2. Implementation path of Industry 5.0

From the evolutionary perspective of the industrial revolution, the implementation of Industry 5.0 cannot be achieved overnight. It needs to be guided by real-world industrial development needs over time and to expand the real value of Industry 5.0 forward on the ground. The following three directions are concluded as the potential implementation path of Industry 5.0.

4.2.1. Blueprint for the development of world industries

As shown in Table 4, governments all around the world have proposed different manufacturing strategies. Based on the blueprint for industrial development in the world, Industry 5.0 will not be completely detached from the current situation of industrial development, thus contributing to the evolution of the path for the realization of Industry 5.0. In turn, the evolution of Industry 5.0 will promote the steady implementation of national industrial development blueprints, thus accelerating the reshaping of the world's industrial system.

4.2.2. Embracing the double-planeness of COVID-19 pandemic

The COVID-19 pandemic was a bi-edged sword, causing a violent impact on the world's industries and accompanied by the opportunity for a change of the times. The global epidemic prevention and control disrupt the structure of the established supply-demand relationships, resulting in inefficient global supply chains and weak value chains,

Table 4
Overview of blueprint for the development of world industries.

Countries	Related strategies	Background and implications
USA	"Advanced Manufacturing Partnership", "Industrial Internet", "Reindustrialization", and "Manufacturing USA"	Defend the global competitiveness of USA manufacturing in hollowing out of domestic industrial structure brought by the "deindustrialization" of the economy.
Germany	"Smart Factory" and "Industry 4.0"	A complete ecosystem for independent development of smart manufacturing will greatly advance the process of Industry 4.0 to Industry 5.0 evolution.
UK	"UK Industry 2050 Strategy" and "Green Paper on Industrial Development Strategy"	The blueprint for modern industrialization is to ameliorate the industrial decline brought about by the "decentralization" strategy.
France	"New Industrial France" and "Industry of the Future"	Help France to promote large-scale economic recovery, thus laying the economic foundation for the move to Industry 5.0.
Japan	"New Industrial Structure Blueprint" and "Society 5.0"	The concept of "Society 5.0" has improved Industry 5.0 and established the concept of human-centric development.
China	"14th Five-Year Plan", and " Long-Range Objectives Through the Year 2035"	Promote the entire manufacturing industry to intelligent, green, and service-oriented upgrades, and accelerate the construction of a strong manufacturing country.

which strongly affect the global economic and industrial recovery.

However, most of the industrial transformations in history have been driven by natural disruptions that threatened public health and safety. This industrial revolution after another has dominated human evolution. The turmoil caused by the epidemic in the industry has highlighted the weak links in industrial development, and many countries have paid more attention to the autonomy and completeness of the industry chain. The anti-risk ability of the industrial system will be improved, which enhances the resiliency of the wider industrial system in the face of global emergencies or production upstream/downstream uncertainties.

This COVID-19 pandemic illustrates the importance of a friendly natural environment and a benign ecosystem for sustainable social development. Under the sustainable development goals, the manufacturing field should seize the opportunity to coordinate actions to solve the contradiction between supply and demand and promote the green transformation of industry. Facing the challenges and opportunities brought by COVID-19 with a cautious and positive attitude and turning passivity into an initiative, we can accelerate industrial recovery and improve the ecosystem, thus promoting the development of Industry 5.0 subtly.

4.2.3. A community of shared future for mankind

With the theme of peace and development moving steadily forward, countries around the world are becoming more and more connected, both in the human and industrial fields. A Community of Shared Future for Mankind (ACSFM), which is a new concept of human society that the Chinese government has repeatedly emphasized, is a potential implementation path to address the common challenges of all humankind.

Building ACSFM in the evolution of Industry 5.0 aims to take into account the reasonable concerns of other countries while pursuing the interests of national workers and to promote the common development of industries of all countries while pursuing the industrial development of their own. There is only one earth for human beings and one world for all countries, and the completion of the world industrial system requires the promotion of ACSFM.

ACSFM stands on a broader perspective, not only focusing on industrial development but also emphasizing the social harmony of the "global village" and the green development of ecological civilization. This is a comprehensive embrace of the human-centric, sustainable, and resilient concepts in Industry 5.0, which will help Industry 5.0 achieve a successful evolution to the fifth industrial revolution. A new feature of the Industry 5.0 era—An Industrial Community of Shared Future may be envisaged.

4.3. Applications of Industry 5.0

When the global epidemic has led to economic recession and various industries are in urgent need of recovery, the concept of Industry 5.0 has not been widely recognized. However, breakthroughs in a new generation of information technology, biotechnology, new material technology, and new energy technology were made at a visible speed. As shown in Table 5, the applications of Industry 5.0 in different fields have been initially explored.

In the healthcare field, personalized medical implants, artificial organs, body fluids, and transplants could be cost-efficiently manufactured by adopting enabling technologies of Industry 5.0 [164]. Scholars proposed a new perspective called Supply Chain 5.0 that aims at adding revolutionary technologies and enabling a super smart and sustainable society [90]. In the education field, the education in Industry 4.0 paradigm is technology-oriented but with Industry 5.0 the motivation is to generate a synergy between machines, robots, and humans [60]. Consequently, a transformation in engineering education to train a new generation of workers for Industry 5.0 is urgent [169]. It is expected to give engineering students the necessary knowledge about collaboration scenarios and machine-robot-machine interaction skills. In a sense, some evolutions such as Engineering Education 5.0 have been a consequence of industrial advances.

Table 5
Applications of Industry 5.0 in different fields.

Fields	Ref.	Typical applications
Smart manufacturing	[60,62]	Cognitive manufacturing; cobots-based manufacturing
Electronics Manufacturing	[128,129]	Rapid printed circuit board prototyping services
Healthcare industry	[88,163, 164]	Cobots-based precision surgeries; health care-connected accurate information-sharing; personalized implants manufacturing
Supply chain management	[60,90, 165] [166]	Human-centric traceability throughout the value chain; Supply Chain 5.0 toward mass personalization; auto-adaptive quality check of pasta supply chain
Shipping industry	[63,167]	Maritime 5.0
Microalgae industry	[125]	Microalgae industry under Industry 5.0
Engineering education	[93,168, 169]	Engineering Education 5.0
Smart cities	[170]	Smart cities under Industry 5.0

5. Limitations, barriers, and challenges

While Industry 5.0 brings many bright visions for the new industrial era, it also faces some problems in the evolution of the industrial revolution. Based on a review of the research limitations, barriers to social progress, and challenges in science and technology, this section mainly explains that the future development of Industry 5.0 will be groping its way through twists and turns, as shown in Fig. 6.

5.1. Limitations of current research

Since Industry 5.0 is an emerging concept, there are few relevant studies available for reference, especially high-quality journal papers. In addition, there are diverse opinions about the evolutionary process of Industry 5.0, which includes: the use of different enabling technologies, the training of workers in the industrial transformation, and the architectural construction of Industry 5.0 systems. This has led to a lack of clear objectives for the construction of the Industry 5.0 architecture and the use of related enabling technologies.

Of course, within the scope of the currently available reference, this paper has tried to achieve in-depth exploration work after absorption/digestion and tried to reduce the impact of research limitations.

5.2. Social barriers

Following the research investigation presented in the previous paragraphs, it has become evident that the evolution of Industry 5.0 will have a serious impact on social systems, and in turn, various factors in society will constrain the development of Industry 5.0, As shown in Table 6, the social barriers could be concluded from four aspects. Firstly, concerning social values, the formation of social values needs time to settle and the right policies to guide them. To enter the Industry 5.0 era, society is bound to undergo a series of transformations, which leads to heterogeneity in terms of social values and acceptance. Ethical issues and moral codes in society will also hinder the human-centric social revolution of Industry 5.0. Secondly， concerning the aspect of the industrial chain structure, the transformation of production tasks in society from technology-driven to value-driven will destroy the structure of the entire social industrial chain, resulting in the emergence of overproduction, which will affect the stability of the value chain and the ratio of supply and demand chains. This hinders Industry 5.0 from accomplishing the goal of moving to a value-driven sustainable development. Thirdly, concerning the Social supervision system viewpoint, The supervision system in the Industry 4.0 era is difficult to adapt to

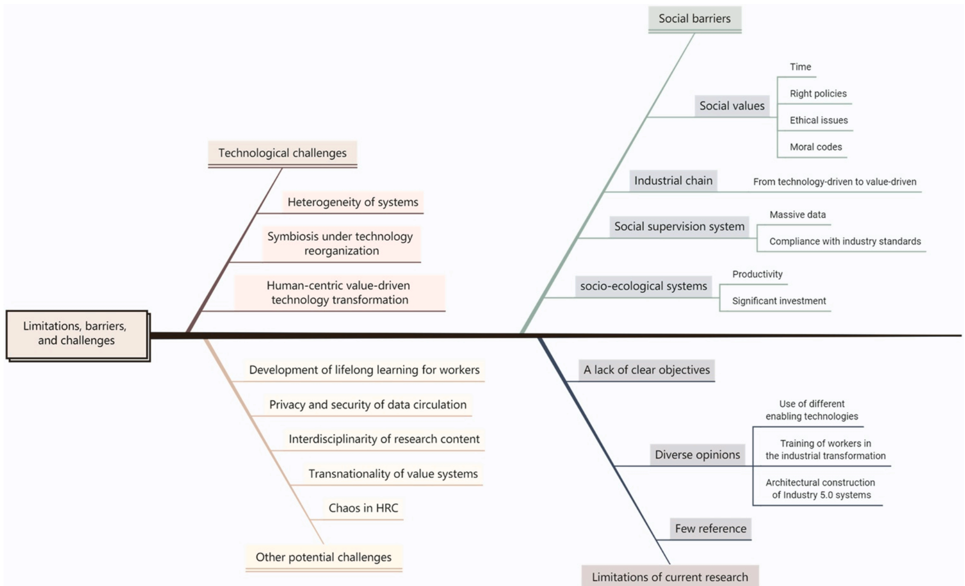

Fig. 6. Limitation, Barriers, and Challenges towards Industry 5.0.

Table 6
Analysis of social barriers to implementing Industry 5.0.

Aspects	Influencing factors	Specific social barriers
Social values	Time, Right policies, Ethical issues, Moral codes	Lead to heterogeneity in terms of social values and acceptance Hinder the human-centric social revolution of Industry 5.0
Structure of the industrial chain	From technology-driven to value-driven	Destroy the structure of the entire social industrial chain Result in the emergence of overproduction Affect the stability of the value chain and the ratio of supply and demand chains Hinder Industry 5.0 from accomplishing the goal of moving to a value-driven sustainable development
Social supervision system	Massive data, and compliance with industry standards	Pose serious challenges to the credible implementation of social supervision
Socio-ecological systems	Productivity, and significant investment	Put tremendous pressure on social ecosystems Lead to tragic and massive destruction of the social ecosystem Contrary to the resilient feature of Industry 5.0

another kind of cognitive and decentralized intelligence in the era of Industry 5.0. The transparency of massive data information flow in cyberspace and the compliance with industry standards pose serious challenges for the credible implementation of social supervision. Finally, concerning a socio-ecological systems perspective, measuring environmental and social value generation requires productivity and significant investment, which puts tremendous pressure on social ecosystems. Further, it may lead to tragic and massive destruction of the social ecosystem, which is contrary to the resilient feature of Industry 5.0.

5.3. Technological challenges

5.3.1. Human-centric value-driven technology transformation

For technology to better enhance productivity for humans and realize human value rather than replace them, there is a fundamental need to transform it into human-centric smart technology. Embedding human-centric values in technology can better serve human beings. In addition, workers in different fields have unique value needs as an independent group, which requires smart technology to be personalized and transformed according to actual application scenarios as a way to adapt to the needs of industrial production.

5.3.2. Symbiosis under technology reorganization

To complete the technology system of Industry 5.0, single technologies cannot just work independently of each other. Because the production paradigm in the era of Industry 5.0 is mass individualization/personalization, the whole process will appear creative in design and complex in manufacturing. This requires different core knowledge of different technologies to complete the support of the whole individualized manufacturing process in a reorganized symbiosis.

5.3.3. Heterogeneity of systems

Smart devices with different technical support have different control systems. Data generation and information exchange within a specific system are supported by individualized algorithms. In addition, systems are characteristically resilient in response and adaptation to disturbing factors in Industry 5.0 paradigm. Taken together, this leads to heterogeneity among differing systems, which is not conducive to cross-platform information exchange and productivity improvement.

5.4. Other potential challenges

5.4.1. Interdisciplinarity of research content

Interdisciplinary convergence brings about the collision of knowledge from different fields and will increase the complexity of research. While promoting the development of new industrial ideas, it also poses a challenge to the diversification of Industry 5.0 systems.

5.4.2. Transnationality of value systems

There are differences and similarities in industrial value systems between transnational or cross-cultural countries. Therefore, how to adapt to the industrial value systems of different countries and the development of each with its characteristics will be a difficult point for Industry 5.0 to gain global consensus.

5.4.3. Privacy and security of data circulation

Human-centric Industry 5.0 will generate massive amounts of data related to human information in manufacturing, and this data will involve a lot of human privacy in HRC. How to ensure security/privacy between devices and networks where data flows will be a challenge for Industry 5.0. This issue will also stimulate the nerves of every worker facing the industrial revolution.

5.4.4. Development of lifelong learning for workers

Adapting technology to humans requires worker training. However, Industry 5.0 involves multidisciplinary and multi-technical knowledge, which raises the demand for well-trained workers and makes training more difficult. In particular, the goal of sustainable development embeds the requirement of lifelong learning in the future development of workers.

5.4.5. Chaos in HRC

The value system of Industry 5.0 will raise the role/status of humans in HRC. If the Cobots that work with humans cannot adapt to the change of roles, it may lead to work chaos, which will bring greater risks to the smooth development of production tasks in factories.

6. Outlook

This section briefly discusses the outlook for future research directions of Industry 5.0, as shown in Fig. 7.

6.1. Characteristics of Industry 5.0

To facilitate the rapid unfolding of the Industry 5.0 blueprint, the unification of Industry 5.0-related industrial and social concepts is imperative. However, this treatment may blur the boundaries of different theories. Subsequent work could be done to obtain a comparative analysis of concepts such as Industry 4.0, Society 5.0, Operator 5.0, and Industry 5.0 to find out the commonalities and dissimilarities between different concepts, which will more accurately reflect the innovation and value of Industry 5.0.

In the white paper on Industry 5.0, EU proposes three main characteristics of future industrial development: human-centric, sustainable, and resilient. Subsequent research can be done based on this proposal and actively explore new features in conjunction with specific application fields, to enrich the connotation system of Industry 5.0.

6.2. Essence of Industry 5.0

In subsection 3.3 of this paper, the authors present and discuss the essence of Industry 5.0 from six perspectives, namely, collaborative intelligence, multi-objective interweaving, multi-technology restructuring, multi-discipline integration, multi-sector symbiosis, and multi-system heterogeneity. Collaborative intelligence is one of the most prominent points in the Industry 5.0 vision. Industrial artificial intelligence in Industry 5.0 emphasizes more on the ability of mutual-cognitive coordination between human intelligence and artificial intelligence in machines to co-innovate, co-design, and co-create individualized products and services. In subsequent studies, we can further choose one of the six points for in-depth exploration, or add a new point to enrich the essence of Industry 5.0.

6.3. Reference architecture of Industry 5.0

This paper presented a tri-dimension architecture of implementing Industry 5.0. This is only a basic architecture given based on the current research status of Industry 5.0, which comes with, the subjectivity of the authors, the transience of the research time, limitations of the research content, and vagueness of the hyper-advance theories. Nevertheless, we believe that this paper has some reference significance for subsequent research. There is no doubt that as the wheel of time runs over the research vein of Industry 5.0, more architectures of Industry 5.0 will spring up. This is where the significance of this paper's architecture lies. In order to achieve as comprehensive an interpretation of the research and implementation of Industry 5.0 as possible, the reference architecture of Industry 5.0 can be summarized in the future.

6.4. Enablers in Industry 5.0

This paper provides an introduction to each of the typical enabling technologies and describes their application in Industry 5.0. The identification of technological enablers is the first step toward implementing

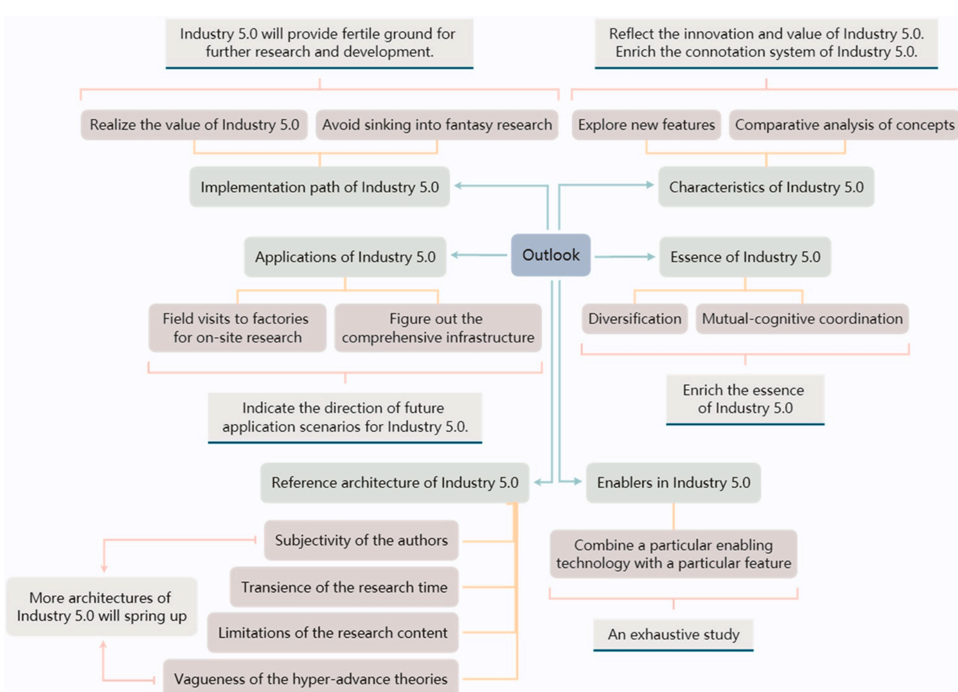

Fig. 7. The outlook for future research directions of Industry 5.0.

Industry 5.0. Subsequent research work can combine a particular enabling technology with a particular feature of Industry 5.0. And then an exhaustive study highlighting the specific application of the technology could be conducted in realizing the goals of Industry 5.0.

6.5. Applications of Industry 5.0

This paper summarizes the Industry 5.0 applications in several fields, but scenarios of how Industry 5.0 will operate in the future are still lacking. It is far from enough to just stop at the theoretical level of research. Subsequent research can be conducted through field visits to factories for on-site research to figure out the comprehensive infrastructure in multiple application scenarios, thus indicating the direction of future application scenarios for Industry 5.0.

6.6. Implementation path of Industry 5.0

Few papers discussed the implementation path of Industry 5.0. This paper is an all-around popularization and discussion of Industry 5.0, but not a detailed in-depth exploration of all valuable directions. The understanding and statements in this paper are only the beginning of the subsequent research, inspiring the researchers to consider how to realize the value of Industry 5.0 in realistic application scenarios and to avoid sinking into fantasy research. Briefly, it is stressed that Industry 5.0 will provide fertile ground for further research and development on existing technologies and techniques, which have been mainly developed under the framework of Industry 4.0. However, instead of focusing on systems, engineers are called to incorporate the human aspect.

7. Summary

On the eve of this dawn when concepts such as Industry 4.0 and Society 5.0 are in full swing, Industry 5.0 thunders out of silence. In this work, we review the evolution of Industry 5.0. We explain the definition of Industry 5.0, the features of Industry 5.0, and the diversified essence of Industry 5.0 from different perspectives. Subsequently, the connotation system and architecture of Industry 5.0 is built, and the key enablers, implementation paths, and future potential applications are discussed. Finally, several limitations and challenges to be addressed, and open-ended suggestions for future perspectives that will help subsequent researchers to better research Industry 5.0, have been explicitly discussed. In summary, Industry 5.0 was proposed to achieve the sustainable development goal of a super-smart society and ecological values, which will become a robust and resilient provider of prosperity in an industrial community of shared future. Concretely, it is expected that this review will generate lively discussions in different fields and attract researchers to join in the pioneering of Industry 5.0, to bring together the efforts of the world to better realize the goals of Industry 5.0.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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