Enhancing Wisdom Manufacturing as Industrial Metaverse for Industry and Society 5.0

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Abstract

Industry 4.0 focuses on the realization of smart manufacturing based on cyber-physical systems (CPS). However, emerging Industry 5.0 and Society 5.0 reaches beyond CPS and covers the entire value chain of manufacturing, and faces economic, environmental, and social challenges. To meet such challenges, we regard Industry 5.0 as a socio-technical revolution based on the socio-cyber-physical system (SCPS), and propose a socio-technically enhanced wisdom manufacturing architecture and framework beyond CPS-based Industry 4.0/smart manufacturing with especially concerning transition enabling technologies such as artificial intelligence, social Internet of Things (SIoT), big data, machine learning, edge computing, social computing, 3D printing, blockchains, digital twins, and cobots. Finally we address the roadmap to blockchainized value-added SCPS-based Industrial Metaverse for Industry/Society 5.0, which will achieve high utilization of resources and provide products and services to satisfy experience-driven individual needs via metamanufacturing cloud services towards smart, resilient, sustainable, and human-centric solutions.

Keywords Social-cyber-physical system · Wisdom manufacturing · Industrial Metaverse · Blockchain · Industry 5.0 · Society 5.0

Acronyms

AI: artificial intelligence
AM: additive manufacturing
CAD: computer aided design
CAE: computer aided Engineering
CAM: computer aided manufacturing
CIM: computer integrated manufacturing
CPPS: cyber-physical production system
CPS: cyber-physical system
DT: digital twin
ERP: enterprise resource planning
GPU: graphics processing unit
HiL: human-in-the loop
HoL: human-on-the-Loop
HofL: human-out-of-the-Loop
ICT: information and communication technology
IbfP: Internet by and for people
IIoT: industrial IoT
IoCK: Internet of contents and knowledge
IoP: Internet of people
IoS: Internet of services
IoT: Internet of things
ML: machine learning
PDM: product data management
PLM: product lifecycle management
SCPPS: social-cyber-physical production system
SCPS: socio/social-cyber-physical system
SF: smart factory
SIoT: social Internet of things
SWSN: social wireless sensor networks
WM: wisdom (wise) manufacturing

1. Introduction

The introduction of the Internet of Things (IoT) in manufacturing has initiated smart factories (Shrouf, et al., 2014). The consequent technology-driven changes have triggered the industrial revolution referred to as “Industry 4.0” (Wikipedia, 2021). Today, the information and communication technology (ICT) including the cyber-physical system (CPS), the Internet of Services (IoS), and cloud computing are being integrated into Industry 4.0. Of these components of Industry 4.0, the CPS is identified as the most prominent and generic (Hermann, et al., 2016), which drives smart manufacturing forward (Kang, et al., 2016) and has been identified as a key research area for industrial automation (Lee, 2015; Leitão, et al., 2016).

Since the first industrial revolution, most products have been made in mass production instead of craft production. Now, mass

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customization and personalization are beginning to emerge, gradually complementing mass production. As customized/ personalized products are closely linked to customer needs and wants, value creation is no longer to be implemented by a producer alone, since it needs a co-creation processing with consumers and designers in the manufacturing value chain. Thus, there is an increasing need to consider human factors in customization and personalization. Further, from the perspective of manufacturing systems, humans cannot be completely substituted, as they supervise and adjust the settings, being the sources of knowledge and competences, diagnose situations, take decisions and several other activities influencing manufacturing performances, and provide additional degrees of freedom to the systems overall (Fantini, et al., 2016). Such capabilities are enhanced in the context of cyber-physical systems (Romero, et al., 2016), which makes it imperative to take humans into account in Industry 4.0 as a socially sustainable manufacturing workforce. As such, in 2021 the European Union proposed Industry 5.0 to complement Industry 4.0 officially presented by Germen at the Hannover Messe fair 10 years ago in 2011, with further consideration of the role and contribution of industry to society by putting research and innovation at the service of the transition to a sustainable, human-centric and resilient industry (Breque, et al., 2021). In fact, the concept of Industry 5.0 can date back to a few years ago (Demir and Ciciba, 2017; Ozdemir and Hekim, 2018).

Furthermore, in 2016 Japan government had proposed a similar but much broader concept, called Society 5.0, which follows the hunting society (Society 1.0), the agrarian society (Society 2.0), the industrial society (Society 3.0), and the information society (Society 4.0). Society 5.0 is a human-centered society that aims to improve human living (Shiroishi, et al., 2018). For the implement of Society 5.0, the role of science, technology and innovation in Society 5.0 were studied (Fukuda, 2020). The importance of artificial intelligence (AI) was introduced (Shiroishi, et al., 2019). In addition to new technologies, the impact of industrial revolutions on the transformation of society, which radically change the social productivity and human life, was also studied (Melnyk, et al., 2019). And the way from industry 4.0 to Society 5.0 was investigated (Salimova, et al., 2019).

As such, there is a strong call in both Industry 5.0 and Society 5.0 to balance Industry 4.0, responsible economic development and resolution of social problems (Potocan, et al., 2021; Zengin, et al., 2021; Carayannis, et al., 2021). Therefore, it is necessary to investigate the manufacturing systems from the perspective of socio-technical view for Industry 5.0/Society 5.0. As being socio-technical by nature, manufacturing should also be studied with the integration of the technical and social systems (Oborski, 2003). Such an example manufacturing model, called wisdom (wise) manufacturing (WM) (Yao, et al., 2014; Yao, et al., 2015; Yao, et al., 2016), was proposed by introducing the Internet by and for People (IbfP, or Internet of People, IoP), Internet of Contents and Knowledge (IoCK), IoT, and IoS (Papadimitriou, 2009) in manufacturing. As a social-cyber-physical production system (SCPPS), WM takes account of both technical and human factors in production, but it still faces challenges such as decentralization, privacy, piracy, counterfeiting, safety, and security.

As the social system integrates humans with the physical devices and the cyber world, human-related data is collected and spread easily. Also, personal data (including physiological information, habits, and social relations) are recorded, which may cause unpredictable issues in privacy protect (Wu, et al., 2014). Conversely, the open innovation, community sharing, makers, prosumers and open sources become part of manufacturing systems to facilitate product innovation for mass personalization.

While information, knowledge and thought can update at an unprecedented speed, piracy and counterfeiting cannot be neglected. The socialization of manufacturing resources endows the public with manufacturing capabilities, but also brings convenience for counterfeiting. What is worse, weapon manufacturing becomes hard to administer. For instance, weapons can be traded in digital files and then printed in distributed 3D printers. Thus, a new balance between open innovation and intellectual property protection should be established. Moreover, software, social media, and other technologies play an increasingly essential role in manufacturing, but also accompanied by threats, such as IT threats, that have not been taken into account by manufactures. As for the SCPS, threats are fatal as they can impact on manufacturing more deeply and broadly. Hence, more proactive approaches are required for safety and security (Tuptuk and Hailes, 2018).

In addition, the convergence of manufacturing, ICTs, and social technologies results in tasks performed in the SCPS context beyond the cognition of workers who were trained for traditional manufacturing with the division of labor. In order to cooperate in cyber, physical, and social worlds, workers are required to have an overall context to complete the interaction. Training and retraining of employees are inevitable.

Compared to other paradigms, the WM/SCPPS promotes the utilization of social information, absorbs collective intelligence through social media/social networking, and allows flexible control and management. Consequently, social problems such as population ageing have to be considered in the SCPS-based manufacturing. Due to the increasing number of older workers, the design of social media and other technologies need to consider the user habits of older workers. Besides, re-education and retraining of older workers are necessary to help them take the use of new tools and adapt to the new environment.

Before, we used to develop manufacturing systems efficiently centered on high productivity especially in the era of mass production. In fact, for developing manufacturing including Industry 4.0 (Zengin, et al., 2021), we need a balance between the natural environment, economic development and social development. And such a balance has resulted in environment-oriented sustainable manufacturing and human-oriented inclusive manufacturing (Yao, et al., 2019). Industry 5.0 is a new emerging manufacturing resultant paradigm of such a balance centered on humans (Breque, et al., 2021).

Now many researchers have joined the research of Industry 5.0. For example, (Xu, et al., 2021) addressed a comparative analysis of Industry 4.0 and Industry 5.0, mainly including its concepts and enabling technologies. (Carayannis and Morawska-Jancelewicz, 2022) conducted a detailed study of society 5.0 and Industry 5.0, and (Maddikunta, et al., 2022) conducted a more detailed and complete overview of the definition, concepts, characteristics, applications and enabling technologies of Industry 5.0. There is also a lot of research related to smart manufacturing, and the metaverse is emerging. However, there are very few discussions on such integration of Industry 5.0, smart manufacturing, especially wisdom manufacturing, and the metaverse.

To enhance SCPS-based wisdom manufacturing to meet such a need, this study develops a view of Industry 5.0 as a socio-technical revolution based on the SCPS, focusing on broadening Industry 4.0 from social aspects and the manufacturing value chain as well as Metaverse. First, we start from analyzing a socio-technically enhanced manufacturing system concerning the three key features of Industry 4.0 (vertical, horizontal, and end-to-end integration). Then, we develop an SCPS-based wisdom manufacturing framework and analyze its key enabling technologies, for a higher utilization of resources and for products and services that satisfy individual needs by manufacturing cloud services that dynamically self-organize socialized and service-oriented production resources. Finally, we enhance the wisdom manufacturing as Industrial Metaverse by borrowing the idea of Metaverse.

2. Revolution from technical to socio-technical

Socio-technical aspects hold that an organization is an integration of both social and technical systems. The social system cannot exist without the support of technical systems, and the changes of technical systems also cause great social influence. An investigation conducted by Trist (Fox, 1995), who has developed the concept of the socio-technical system, shows that most industry problems result from the lack of adequate attention to the social impact of technical systems. Further, the socio-technical approach had been developed to describe and manipulate human beings (Oborski, 2003). Thus, the study of Industry 4.0/5.0 should also be extended to include the social aspect.

The correspondence between the industrial and society transformation is shown as Fig.1. In general, industrial revolutions bring changes to human society, provide the driving force for society development, and accelerate the transformation of society. In Society 1.0 and 2.0, industry revolution did not happen yet, but social transformation had taken a long time. When the first industrial revolution occurred, the society moved to the third stage. After Industry 3.0, the society rapidly transformed into an information stage. The advances in ICTs such as IoT, IoS, and big data, as well as in new advanced manufacturing technologies such as 3D printing and reconfigurable manufacturing, enhance manufacturing productivity and flexibility greatly, resulting in Industry 4.0 in the form of CPS, which enables mass customization and even mass personalization. In fact, Industry 4.0 consists of a long-tail production with focus on mass customization and personalization (Yao, et al., 2018) and needs collective intelligence and wisdom such as crowdsourcing, knowledge sharing, innovation, and co-design of products by both producers and customers or users. Industry 4.0 and 5.0 promote the society moving toward a super smart stage - Society 5.0, which we call wise society. Industry 5.0 or Society 5.0 is characterized by human-centric customization/personalization in the form of SCPS.

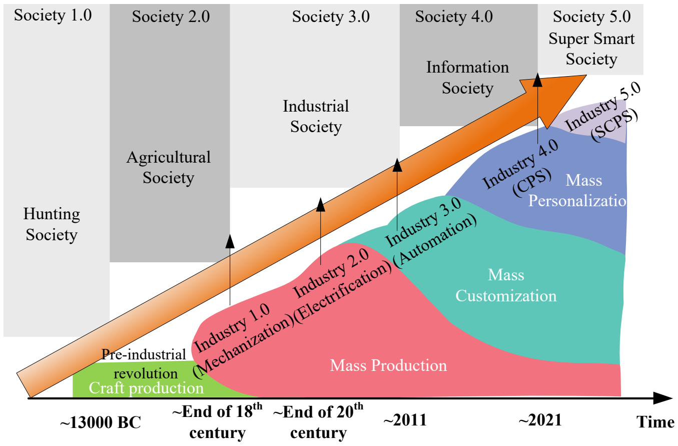


Fig.1 Society transformation and industrial revolutions

Modern manufacturing systems use the Internet as a tool to integrate data, information, and knowledge. Over the past decades, the Internet has dramatically transformed social technologies toward user-driven technologies (as shown in Fig. 2). As a result, users can tag, share, and generate contents through Internet (such as Wikipedia, YouTube, and Facebook). Global communities are established for users to learn and share knowledge together, and to publish their opinions. Thus, enterprises need to embrace the new technologies to listen to the voice of their customers and converse with them through social technologies. Moreover, platforms should be built for absorbing customer ideas, thoughts, creations and innovations.

In particular, with the rise of Web 2.0, social networking tools, IoT and cloud computing, Enterprise 2.0, crowdsourcing, open innovation, and cloud manufacturing were born. Later in Web 3.0, smart factories and Industrial Internet were emerging. Further, IoT is being extended to a social one (Atzori, et al., 2012), resulting in big data linking the physical, cyber and social worlds together. Moreover, the Internet focus is shifting from information to value with the advent of blockchain technology that facilitates value-exchange peer-to-peer without the need for an intermediary. As the new industrial (r)evolution shifted from the previous focusing on technical aspects to one that emphasized both technical and social aspects, wisdom manufacturing in the form of SCPS came into being (Yao and Lin, 2016). Therefore, it is necessary to study Industry 4.0 as a socio-technical revolution based on the SCPS (Yao, et al., 2019) instead of the CPS (Mosterman and Zander, 2016; Lee, et al., 2015; Lu, 2017; Wang, et al., 2015). To complement technology-driven Industry 4.0, going beyond producing goods and services for profit, Industry 5.0 is emerging to account for environmental and societal costs and benefits as well, with human-centricity, sustainability and resilience as its core elements, shifting from the shareholder value to the stakeholder value (Breque, et al., 2021) and from technology-driven to value-driven (Xu, et al., 2021). Such human-centric value-driven manufacturing will be enabled by the Industrial Metaverse as stated below.

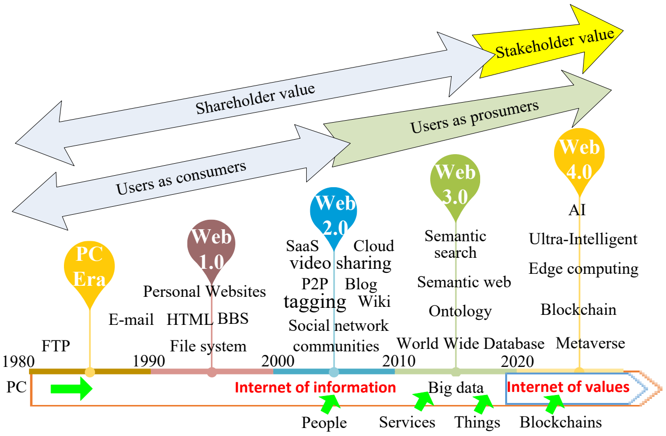


Fig. 2 Internet evolution that influences the manufacturing value chain

From the technical revolution view, components of Industry 4.0 include IoT, CPS, IoS, and Smart Factory (SF) (Hermann, et al., 2016). More specially, the IoT provides connectivity for anything from anytime, anyplace and anyone (Atzori, et al., 2010); the CPS integrates the physical processing and computation into a whole; the IoS encapsulates resources as services and allows users dynamically to combine services in an ad hoc manner. Based on the IoT, CPS and IoS, the SF is realised as a factory that is flexible, transparent, efficient, and profitable (Wang, et al., 2016; Chen, et al., 2017). Such a view of Industry 4.0 focuses on the adoption of the CPS and related new technologies.

Industry 4.0 is characterized by features that inherently contain social attributes as shown in Fig. 3: 1) vertical integration that integrates systems at different hierarchical levels, 2) horizontal integration through value networks that integrates systems internal and external, and 3) end-to-end integration across products' entire value chain and incorporates customer needs (Kagermann, et al., 2013).

Vertical integration focuses on the integration of the various systems of a factory with different hierarchical levels (e.g. actuators, sensors, control, execution, production management and planning levels), which makes the overall system flexible, automatic and reconfigurable. In such an integrated factory, tasks of humans are moving from simple manual tasks to decision ones, and the abilities of employees are amplified in the context of a cyber-physical system (Romero, et al., 2016) and social networks (Moghaddam and Nof, 2017). While most of the current researches aim to take the advantages of new-generation ICTs, for example, by using the computational, communication and control techniques to achieve a CPS, human factors also need to be studied to accommodate with the ever-increasing variability of production. Further, social networking inside a company can increase the involvement and promote employees to take advantages of their skills and experience.

Horizontal integration refers to the integration of the different stages of manufacturing and business planning processes through value networks that involve an exchange of materials, energy and information both inside and outside a company. In other words, modern manufacturing factories are becoming highly distributed but interconnected, driven by globalized economics and competitiveness (Moghaddam and Nof, 2017). Furthermore, with the emergence of personalized production, varied products are produced in low volume, arousing the need for enterprises to reorganize internal and external production resources to meet the diverse needs of customers. Thus, collaboration inside a company or among companies must be augmented. To build such collaboration, on one hand, the CPS, IoT, and IoS need to be introduced into modern manufacturing to connect the information islands of enterprises to achieve information exchange and servitization of resources, and form the cooperation cross-sectorial, cross-disciplinary, and cross-regional in a dynamic way. Thus, the social system must be taken into consideration as well to build a reliable relationship among departments, companies, organizations and individuals, and efficiently to interact based on resource networks and friendships. Thus, external resources can be organized efficiently based on social technologies. Furthermore, resources can aggregate and self-organize based on market and interest. Therefore, social attributes, which reflect the social relation of nodes, need to be added to enhance the system. Besides, social networks can be utilized for service advertisement, discovery, and assess. Thus, the socialization of resources by the emergence of new technologies, new value networks and new business models promotes the achievement of horizontal integration of Industry 4.0, and boosts the development of reliable, efficient and sustainable manufacture (Stock and Seliger, 2016).

End-to-end integration goes through the entire value chain of products and needs to cover every aspect from customer/client requirements to manufacture of the final products and services. Such integration means that customers can no longer only choose from a predefined range of products, but instead, they are able to take part in the full product life cycle to meet their individual needs or create their products. The value creation is no longer to be implemented by a company alone, since it is a co-creation process with consumers. Therefore, the information that customers put on Internet impacts the supply chain and manufacturing activities (Esmaeilian, et al., 2016). Consumers in the manufacturing value chain becomes an indispensable part of the manufacturing process, as they can not only put forward personalized needs, but also provide individual data, and even personalized design for production. Moreover, the term "prosumer" is coined for a person who consumes and produces products. And even, products can be "designed and produced" by a consumer, and then sold to other consumers, so the maker culture motivated by fun and self-fulfilment is becoming popular (Anderson, 2012).

In summary, with the emergence of new technologies and evolution of manufacturing paradigm, the distance among humans or companies gets shrunk, the conventional relationship between home and workplace gets further eroded, and the distinction between producers and consumers gets blurred.

Therefore, CPS-based Industry 4.0 should be extended to SCPS-based to realize customer relationship management, and to absorb customer ideas, thoughts and innovations for mass personalization. In this sense, social media provide a novel way to support customers to involve in the full life cycle of products.

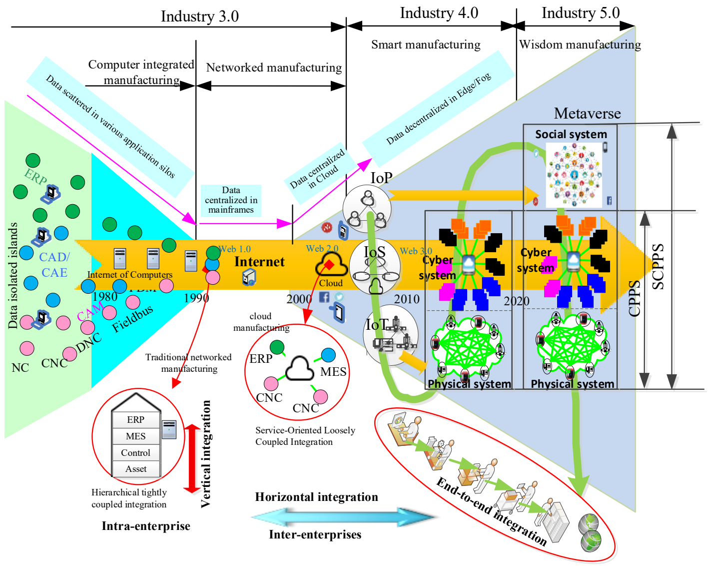


Fig.3 Manufacturing paradigm shifts along with the Internet evolution and emerging ICTs

Customers can submit their needs and track the production process by using social media through the Internet, and then comment and share their experience or knowledge in their communities. Through social media, achievements, which are unimaginable for companies, have been made by the IoP such as Wikipedia and YouTube. Similarly, social media expand the source of business innovation, which provides a great potential for mass personalization. To better fulfill the key features of Industry 5.0, manufacturing systems should be developed from the point view of SCPS beyond CPS, to achieve an overall optimization of manufacture systems and satisfy human needs (Jing and Yao, 2019). At present, research has been undertaken on the socio-technical aspect in manufacturing. For example, Tortorella et al. (Tortorella, et al., 2017) have developed an assessment method with regards to SE (socio-technical and ergonomics) practice adoption for improving the work environment of workers in lean manufacturing.

3. Enhancing wisdom manufacturing for industry/society 5.0

Wisdom manufacturing was firstly coined by combining the four networks (IoT, IoS, IbfP/IoP and IoCK) with manufacturing in 2014 (Yao, et al., 2014), then as a socio-technical system or SCPPS to study (Yao, et al., 2015; Jing and Yao, 2019). Wisdom manufacturing has been developing along with the development of new-generation ICT and AI (Ma, et al., 2022), and used in big-data driven proactive manufacturing (Yao, et al., 2017), inclusive manufacturing (Yao, et al., 2019), and autonomous smart manufacturing (Yao, et al., 2022). In fact, the wisdom manufacturing is a hypernetwork composed of a physical network (IoT), a cyber network (IoS), a social network (IoP) and a linking network (IoCK) as shown in Fig. 4.

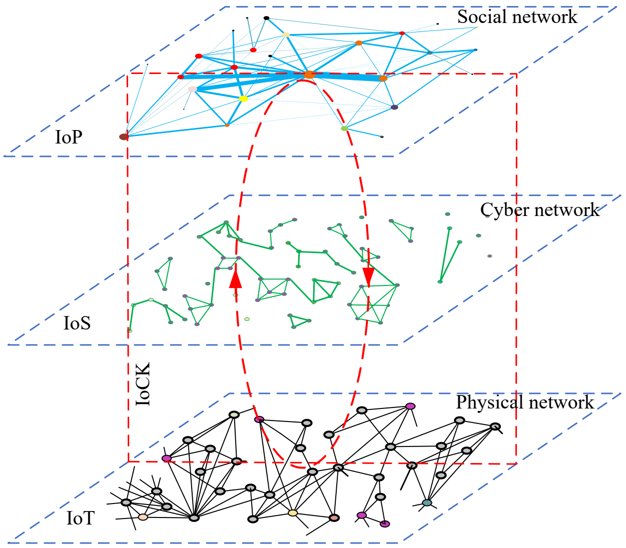


Fig. 4 Hypernetworked wisdom manufacturing

3.1. Wisdom Manufacturing Reference Architecture

Figure 5 illustrates a three-dimensional wisdom manufacturing reference architecture. In the Interoperability Layers dimension, there are six abstract layers: Asset, Communication, Data, Function, Business, and Users from bottom to top, which correspond to six organization semiotics levels: Physical, Empiric, Syntactic, Semantic, Pragmatic, and Social, respectively. The social cyber physical (production) system, shortened as SCP(P)S, is consisted of the six Interoperability Layers or Semiotics Levels, two layers/levels of which, in turn, consist of the physical, cyber and social (sub)systems, respectively. In the System Levels dimension, there are Production, Field Device, Station, Production Line, Enterprise, and Connected World. And there are Design, Production, Usage, and Recycle in the Product Life Cycle dimension.

There are two kinds of core technologies to enhance wisdom manufacturing for Industry 5.0/Society 5.0: AI and blockchain, as stated bellow. Enable technologies is addressed in next section.

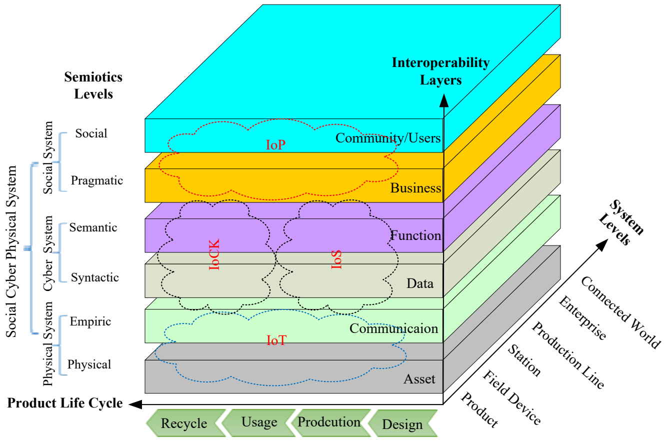
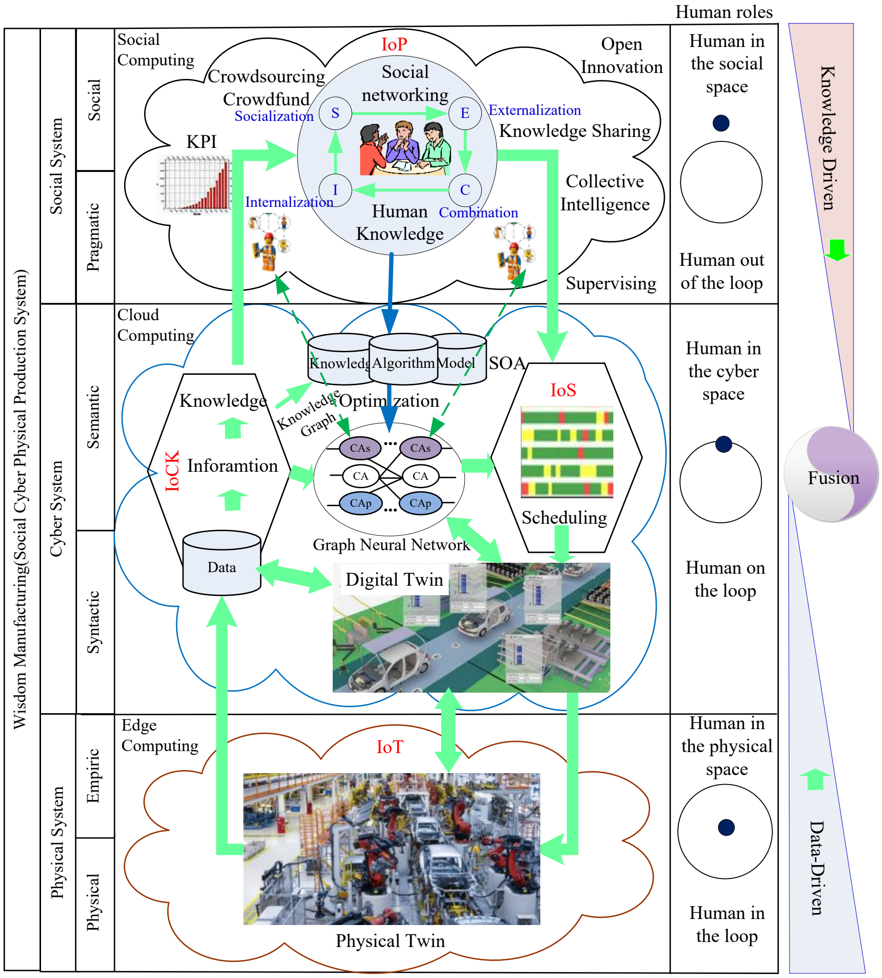


Fig. 5 Wisdom manufacturing reference architecture

3.2. Data-and-Knowledge-driven SCPPS Framework

To take advantages of new-generation AI, a data-and-knowledge-driven mechanism is necessary. On the one hand, data-driven methods represented by deep learning and big data can perform cognition, memory, and correlation analysis. However, data-driven methods lack the ability of inference, logical reasoning, and explanation, require a huge amount of data for training, and are unable to handle tasks with complex spatiotemporal relationship. On the other hand, while the knowledge-driven approach represented by symbolic representation can perform logical reasoning and inference, it is not suitable for processing unstructured data such as images and audio. Thus, in the complex manufacturing systems, it is necessary to combine both methods, and even further integrate reinforcement learning to form a deep reinforcement learning model that incorporates prior knowledge.

As mentioned, modern manufacturing systems are complex systems including social, economic, environmental, and other factors, which have moved from the computer integration system to the collaboration of human, machines and things, as shown in Fig. 6. In the SCPS architecture consisted of three-subsystems, the physical system with the smallest time scale realizes autonomous intelligence and multi-sensor perception intelligence (cross-media intelligence) through IoT and edge computing which involves moving part of the computing load to the edge of the network to take advantage of currently untapped computing power in edge nodes such as base stations, routers, and switches (Varghese, et al., 2016); the cyber system with a moderate time scale implements deep learning and data intelligence, and provides cloud manufacturing services on demand through IoS and IoCK; and the social system with the largest time scale enables people to participate in product design/production and services anytime and anywhere through IoP. As such, the integration of people, knowledge and crowd intelligence is realized, and further collaborated with other levels to form hybrid enhanced intelligence. It can be seen that this reference architecture can not only embed a priori knowledge in a deep (enhanced) neural network in the form of a graph network representation making the AI model explainable, but also integrate emerging AI technologies such as autonomous intelligence, multi-sensor perception intelligence, data intelligence, crowd intelligence and hybrid enhanced intelligence into one, forming a humans-machines-things collaborative smart manufacturing system with multi-subject, multi-level, multi-scale, cross-domain, and hypernetworked.



CA-Cyber Agent;CAp-Cyber Agent for physical things;CAs-Cyber Agent for social beings;

PA-Physical Agent; SA-Social Agent;

Fig. 6 Data- and-knowledge-driven wisdom manufacturing framework

Specifically, the mechanism of SCPS based new-generation AI can be depicted follow: In the physical system, data in production is collected by IoT and transformed to the cyber space where data-driven methods such as deep learning are used to extract rules and knowledge in the data. On the other hand, the knowledge of experts is converted into data for decision-making in production process. And knowledge-based methods are used for logical reasoning and inference. Such combination of data and knowledge makes the AI model explainable and realizes knowledge extraction automatically. In other words, the manufacturing system has the ability of learning, cognition and knowledge generation. Some decision-making processes, which are completed by humans traditionally, can be achieved by AI or the collaboration between AI and experts. Thus, manufacturing systems can deal with complexity and uncertainty, manufacture varied products flexibly, and satisfy personalized needs in Industry/Society 5.0.

3.3. Blockchainized Wisdom Manufacturing Framework

A layered framework for wisdom manufacturing enhanced by big data, edge computing, and blockchains, is shown in Fig. 7. This framework forms an SCP(P)S that integrates social, cyber and physical systems as a whole. As such, an integrated manufacturing system evolves into a customer-centric, service-oriented, value added, blockchainized, and data-and-knowledge-driven system.

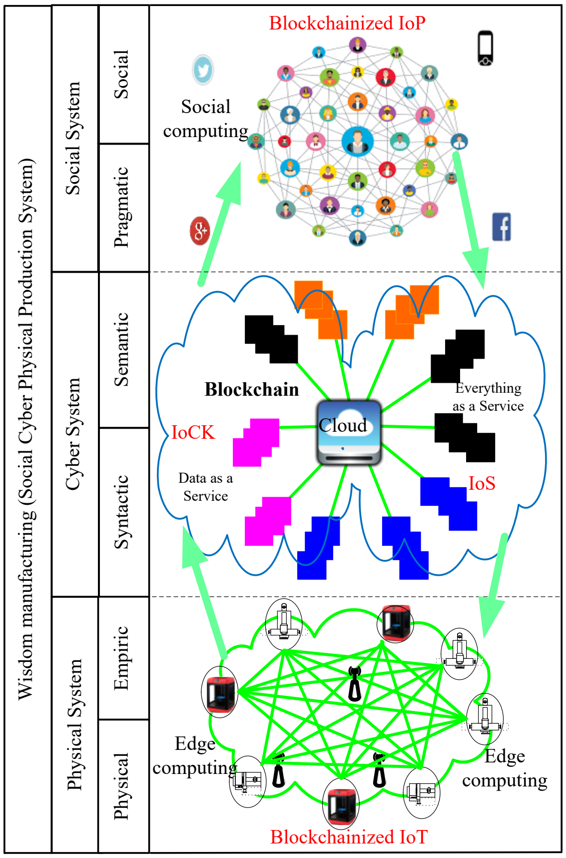


Fig. 7 Blockchainized wisdom manufacturing framework

The social system is composed of people, organizations, and communities, and linked by IoP with focus on human interaction, tacit human knowledge, collective intelligence, and social intelligence, as well as knowledge diffusion, innovation, social needs, culture, law, and value exchange. The physical system is composed of workshops, machines, sensors, and other equipment or resources, which are the executors of manufacturing tasks, and linked by IoT with focus on the connection and perception of heterogeneous resources in the real world to form an environmental intelligence. The cyber system is consisted of IoCK and IoS with focus on the processing and sharing of data and information, especially knowledge mined from big data, machine learning, and AI, and maps the real world (including physical and social systems) to the virtual world. The fusion of cyber and physical systems results in a CPS where the physical processing is synchronized with the computing processing, and the further integration of the social system forms an SCPS where machines/computers, things/environment and humans coordinate with one another.

IoP brings highly efficient interaction between humans, companies, as well as customers and companies based on social media and social networks, which provide great support for the design, decision and planning in the cyber system, and become an indispensable source of the knowledge and innovation for the IoCK. Heterogeneous resources in the real world are encapsulated as services in the cyberspace and used on demand by customers, thus crossing platforms, disciplines, and even areas through the IoS. This means that the IoS can break the boundaries among resources in the real world, reduce the cost of connection, increase the sharing rate of resources, and improve the utilization toward a sustainable development. For example, cloud computing shares its computing resources and data to others on demand. Conversely, IoCK provides enabling technologies for dealing with large amount of data produced in the social, cyber and physical worlds. By connecting and perceiving things in the physical world, IoT transfers them into the cyber system. It lays a solid foundation for the implementation of CPS/SCPS. Moreover, human behaviors become appreciable with the introduction of smart phones and wearable devices, and social-media based social sensors (Kompatsiaris, et al., 2013) of human beings reveal valuable insights, which usually is not possible with existing, limited, controlled, and laboratory-based datasets. The introduction of social attributes (Atzori, et al., 2012) in IoT results in the so-called social-IoT (SIoT), which provides a connection for the SCPS, and widens the data sources of the cyber system. Furthermore, human beings, machines, and other resources can be modeled as smart agents with attitudes of belief, desire and intention (Jing and Yao, 2019).

Due to the integration of SCPS, disruptive changes have occurred in all aspects of the manufacturing system including design, manufacturing, assembly, distribution, and business model. Such an example is 3D printing, in which a complex part can be completed in one process without complex and time-consuming assembly processes, and at the same time the accuracy of parts can be improved to meet individual needs (Calì, et al., 2012). Unlike traditional scheduling for mass production, 3D printing focuses on the production for individual needs and deals with non-identical products in low volume and high variety. Although 3D printers are batch-processing machines, they are scheduled mainly on the basis of the equipment capacity being simplified to one-dimensional values like weight, volume, quantity or area, and corresponding resulted capacity cost for parts (Zhang, et al., 2020). Faced with social manufacturing, scheduling in 3D printing needs to introduce irregular parts packing technologies to handle with varied parts for improving production efficiency and application promotion.

4. Key enabling technologies

As depicted in Fig. 8, Industry 4.0, which is studied usually as a CPS from a technical viewpoint, can be extended to a social-cyber-physical system from a socio-technical viewpoint. Such an SCPPS is customer-centric and service-oriented to meet customized/personalized needs. Resources in the SCPPS are distributed geographically and physically, but they can be flexibly reorganized on demand tightly when linked in the cyber system. Based on such a viewpoint, decentralized and distributed production, communication and management technologies, and high-performance computing processing power need to be addressed to support the development of complex and diversified SCPPS. For this purpose, this section investigates the cutting-edge enabling technologies for integration to the SCPPS.

4.1. IoT/SIoT/IIoT

As IoT provides connectivity for anything at anytime, anyplace and anyone (Atzori, et al., 2010), focusing on supporting the interconnection between machines for sending data to each other and interaction, SIoT (Social Internet of Things) is proposed to further integrate the social network for supporting novel applications and networking services for the IoT in more effective and efficient ways (Atzori, et al., 2012). Further, SIoT is also used for connecting with human and defining human behaviors (Jara, et al., 2014). Besides, the application of IoT in industry has posed a large impact on manufacturing business models (Kiel, et al., 2017), which has resulted in the so-called industrial IoT (IIoT), or the Industrial Internet.

By introducing social networking that establishes social links as humans do, SIoT allows objects to have their social networks. In addition, social wireless sensor networks (SWSN) were proposed to provide the sociality of the services over wireless sensor networks (Kim, et al., 2016). As a result, SWSN can simplify the navigability in a dynamic network of billions of objects, promote robustness in the management of the trustworthiness of objects when providing information and services, and improve efficiency in the dynamic discovery of services and information. Furthermore, SIoT allows humans to impose rules to protect their privacy. Specifically, social attributes such as friendship and trust can be established among objects. Then objects can only have connection permission to their social network.

Conversely, to define human behaviors, social sensors have been developed to collect invaluable customer requirements, social context, and physical sensor data, and incorporated in the cyberspace (Ding and Jiang, 2016). For example, the use of smart phones and body sensors makes human status appreciable. Consequently, valuable insights that are not available previously can be obtained.

In short, as the social system is considered as an indivisible part of Industry 5.0, the introduction of SIoT to integrate social networks and perceive human states is necessary. Further, the social attributes are required to facilitate the communication between humans and objects.

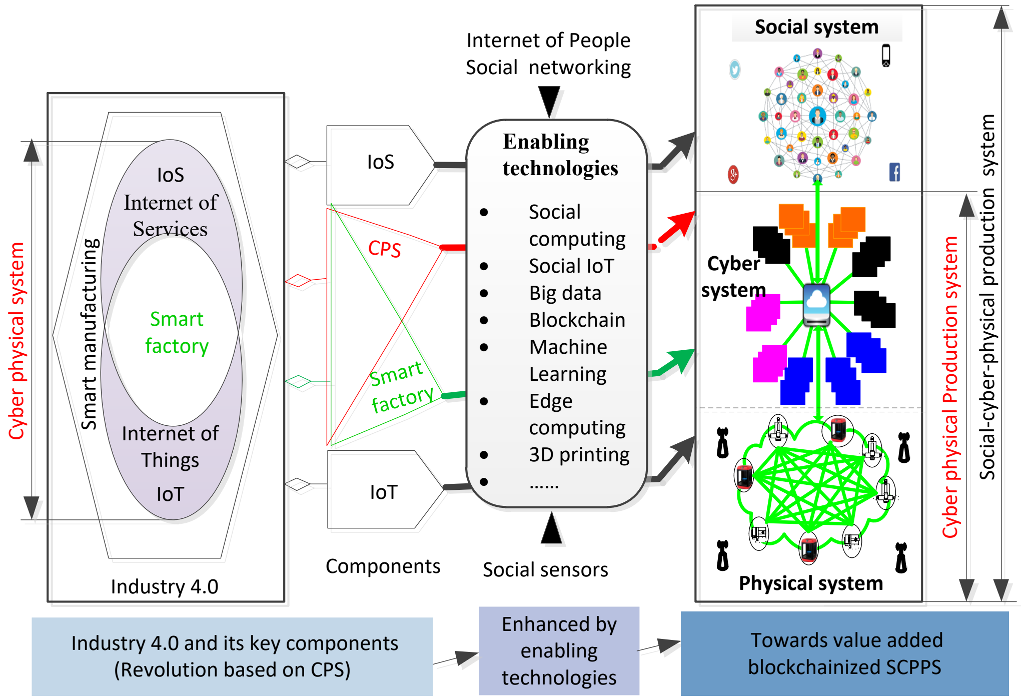


Fig. 8 CPS for Industry 4.0 being extended to SCPPS by the key enabling technologies

4.2 Big Data

Owing to the socialization, digitization, personalization, interconnection, and servitization of industry, big data is emerging in manufacturing systems. For example, as discussed, the introduction of IoP, IoT, and IoS in WM produces massive data with various unstructured types, which brings the challenges of 4V (Volume, Velocity, Variety and Value) of big data to manufacturing enterprises. Specifically, massive humans-related unstructured data is produced by the IoP (including social networks and mobile Internet); Product-related data is produced during the design, emulation and simulation especially for the mass personalization, and digital tools such as CAD, CAM, CAE, PDM, and ERP are used; Data streams are continuously generated by sensors and smart objects in monitoring of production based on IoT/SIoT/IIoT. In effect, massive data exists at all stage of the entire life cycle of products, and throughout the manufacturing value chain. So, the use of such big data will be the basis for future competition and growth of manufacturing enterprises (Yao, et al., 2017).

Data-intensive computing science, represented by big data, has been regarded as the fourth paradigm for scientific exploration after the first paradigm - empirical, the second paradigm - theoretical, and the third paradigm - computational (Hey, et al., 2009). Nowadays, the dramatic increase in data quantity gives birth to an emerging paradigm of research - data exploration: data is collected through the experimental equipment or generated through simulations, and then meaningful information or knowledge is extracted and stored for researchers with the help of computers such that the empirical, theoretical and computational paradigms are integrated. This indicates that enterprises need to explore big data either from the view of the manufacturing development or the view of market requirement, along with the awareness of the big data importance in manufacture enterprises. In fact, the initial attempts have been conducted in varied segments such as equipment maintenance, production fault detection and classification, fault prediction and predictive manufacturing. However, this work is still in its infancy, and the data-driven manufacturing needs to be further expanded both in depth and in breadth, especially shifting focus on monitoring to optimization (Magoutas, et al., 2014).

As discussed by Kusiak, smart manufacturing must embrace big data (Kusiak, 2017). To achieve data-driven manufacturing, it is necessary to use the data as an input. Then, real-time feedback, production monitoring, simulation and business process optimization can be realized. In fact, big data exists in product lifecycle (Li, et al., 2015), and its applications "span different fields such as customer need identification, risk management and decision-making, data-driven knowledge, product and service design, quality management, and opportunity recognition and creation" (Urbinati, et al., 2019).

In short, big data can bring benefits to the entire value chain. To this end, big data must be processed adequately to support machines to learn and help users to make decision.

4.3. Machine Learning

Just as Alpaydin described, stored data become useful only when they are analyzed and turned into information for application (Alpaydin, 2010). More specifically, the data-driven machine learning (Michalski, et al., 2013), which can find highly complex and non-linear patterns by transforming raw data to features spaces, can be applied to prediction, detection, classification, regression, or forecasting (Wuest, et al., 2016). Recently, the flourish of machine learning (specifically deep learning and reinforcement learning) provides a practicable way to deal with such large amount of data. Thus, the introduction of machine learning (ML) in manufacturing system would provide the following advantages:

1) ML can deal with high-dimensional data. As varied sensors and integration of SCPS in manufacturing generate a huge amount of data of high dimensions, it is difficult to understand or find a relationship by traditional data-mining methods.

2) ML has the ability to learn and adapt. As a manufacturing system faces external unpredictable events and internal complexity, the predefined model set by humans becomes powerless in dealing with uncertain events. So ML, which can learn from the data by itself, provides a feasible way to dynamically respond to such challenges.

3) ML is able to derive knowledge. While data available explodes in manufacturing systems, knowledge for decision-making does not grow synchronously. By learning from big data, knowledge can be derived from manufacturing systems that were data-rich but knowledge-sparse.

In short, wisdom manufacturing can be regarded as the integration of networked manufacturing and advanced AI, and the usability of ML approaches and the availability of raw data increase the applicability of AI in manufacturing. Consequently, the introduction of big data and ML makes manufacturing shift from reactive to proactive (Yao, et al., 2017).

4.4. Edge Computing

Big data processing requires not only an efficient model (e.g., deep learning) in software, but also computing power in hardware. Although centralized cloud computing with powerful computing power provides computing resources for users on-demand (Marston, et al., 2011), the realization of cloud computing depends on the efficiency of network transmission. Long-distance transmission results in high delay and bandwidth consumption. This limits the development of CPS/SCPS where massive data is required to be processed in real-time (Yao, et al., 2017). On the other hand, pervasive computing or IoT based on embedded computing provides a way to process real-time data in manufacturing. However, with the limitation of cost, volume and power of sensors or other smart devices, it is expensive and unrealistic to equip high computing power in each object. What is worse, as the frequency of use and the peak value of computing demand are varied, it is a waste of resources if every device is equipped with full computing power. Therefore, there is an urgent need to introduce edge computing in Industry 4.0/5.0 as there are innumerable and variable devices in the SCPPS. Edge computing can balance the conflict between computation offloading and real-time requirement and play a key role in a complex manufacturing environment.

In fact, edge computing is a model for enabling computation and storage resources at the proximity of subscribers to serve delay sensitive and context-aware applications (Shi, et al., 2016; Ahmed and Ahmed, 2016). Such a computing example is a smartphone between body sensors and cloud, or a gateway in a smart factory. Edge computing can be viewed as a bridge between pervasive computing and cloud computing, to make up for the insufficiency of cloud computing and pervasive computing. Compared to a traditional central control node responsible for managing other nodes, edge computing is more like a collaborator that provides computing power and storage resources on demand. More specifically, edge computing brings the following benefits to the WM/SCPPS:

1) Manufacturing system's real-time responsiveness can be improved and transmission load can be lightened. With the expansion of Industry 4.0 based on CPS, the number of resources connects to manufacturing systems are exploded. As enormous raw data will be produced continuously, thus real-time processing is required. As responsiveness plays a vital role in manufacturing to deal with abnormal events, distributed edge computing, which is closer to demand and cuts down the transmission time, provides a solid foundation. Besides the reduction of latency, computing in local instead of in cloud can save a huge expenditure for transmission and lighten the bandwidth load.

2) Edge computing can provide better security and privacy protection. As we introduce the social system into wisdom manufacturing, private-sensitive social data becomes a significant part of industrial big data (Yao, et al., 2017). For example, in mass personalization individual data is not only the foundation for design, but also for company competitiveness. The security and privacy protect become more and more important. Conversely, data stored in the cloud may be indirectly analyzed by service providers. Further, data transmission to and for cloud increases the additional risk of data leakage. Local edge computing, on the other hand, avoids the leakage of information, remote attacks and other potential hazards by the use of local storage and computing. Besides, data pre-processing before upload in edge servers can remove private information from data and avoid a leakage during transmission.

3) Edge computing can provide personalized computing power. As a result of a wide range of manufacturing resources, the structures of manufacturing data are also varied. Therefore, before processed, data needs to be normalized for cloud computing. It is inefficient for a centralized cloud service to normalize varied data. Instead, edge computing can use a dedicated processor and processing model to achieve efficient data processing accordingly. For example, faced with an image processing scene, the use of dedicated GPU processors, can not only save computing costs, but also improve processing speed.

Thanks to edge computing pre-processing data, the reliability of data can be improved, and the unnecessary transmission and computation can be reduced.

4.5. Social Computing

Except for the dramatically transition of engineering systems, technologies bring profound impacts to the social structure over last decades as well, resulting in a more dynamic, faster, and broader social system with openness and more interaction. In addition, as the vital part of a manufacturing system mentioned above, the social system changes the way of marketing, production and management of manufacturing enterprises, for example, changing employees' abilities and customer relationship. Hence, social computing, which aims at solving complicated problems by integrating social and computational systems together (optimization of both technical and social aspects), must be conducted for the WM/SCPPS to improve system performance. Although social computing has not yet had a unified definition, related-research mainly focuses on two aspects: one is centering on the use of computing technology to improve the quality and efficiency of social interaction, such as social media, social networks, wiki, blogs, etc.; the other is applying the sociology and anthropology knowledge to the computing process to analyze social problems, including prediction market, crowdsourcing, and collective intelligence (Wang, et al., 2007; Parameswaran and Whinston, 2007). For example, information produced by a group of people is used to support the function of a system, as ranked based on user commentaries.

The introduction of social computing in the WM/SCPPS can avoid the social risk to achieve sustainable manufacturing, resulting in better use of new social technologies for the production process and management, and provides effective decision-making and technical support. In addition, the ways of enterprise innovation are broadened, and innovation ability is improved (Yao, et al., 2015).

4.6. Additive Manufacturing/3D Printing

Additive manufacturing (AM) or 3D printing, used interchangeably, refers to the method of creating 3-dimensional objects from digital models layer-by-layer under computer control (ASTM, 2015), which is currently being lauded in the popular press as a potential socially transformative manufacturing technology. It opens up new opportunities for economy and society, which facilitates customized production and allows designs that are not feasible with traditional manufacturing techniques (Thomas and Gilbert, 2014). Based on the cost model (Hague and Ruffo, 2007; Ruffo, et al., 2006), 3D printing shows unprecedented benefits and potential in low volume production.

Instead of tedious processes, 3D printing leads to free-form product design and fabricates directly based on digital models with the characteristic insensitive to the sophistication of geometric shapes. Thus, personalized production costs and the threshold of public participation are reduced. In this sense, 3D printing enables public participation in manufacturing with abilities to realize their ideas and provides a fundamental for social manufacturing. Manufacturing innovation is no longer just the privilege of professionals. Instead, everyone is capable of enjoying the progress of manufacturing. As a result, social manufacturing becomes a part of modern manufacturing.

Further, AM is technically a viable form of distributed manufacturing which can be deployed in distributed and shifts production closer to customers even in customers' home. Hence, inventory and transportation costs can be diminished by replacing logistics with the digital transmission and make-to-order strategies. In addition, AM has the potential to reduce the number of stages in the traditional supply chain (Huang, et al., 2013).

Therefore, AM can be regarded as socialized manufacturing, which also shows a great potential benefits for the sustainable development of manufacturing industry from an ecological perspective (Kreiger and Pearce, 2013). Wang (Wang., 2012) has proposed a social manufacturing, in which customers can participate fully in the whole life cycle of production processes and realize personalized production, based on the combination of 3D printing manufacturing networks, social networks, Internet, and logistic networks. In such a social manufacturing system, the so-called prosumers or makers become a common part of the manufacturing system. An example is Shapeways, a 3D printing service provider, who transforms users' designs into products and create a marketplace for their designs. In such a new model, consumers evolve as prosumers, which blur the roles of producers and consumers. Further, a manufacturer is also becoming a developer platform and a marketplace for its prosumers.

4.7. Blockchain

Although social factors have been introducing into manufacturing systems, and manufacturing resources have been socialized, social interactions among manufactures, customers, and prosumers require extremely trust between each other. Without trust, social interactions are difficult to carry out. Further, social factors or socialized resources are unable to play their role. To build such a trust system always costs a lot of time and resources in traditional ways. Recently, the application in the cryptocurrency bitcoin, the first digital currency that is issued and backed by users rather than a central authority, shows the benefits of blockchains to build a transaction system without trust among users. The potential benefits of blockchains are more than just in economic (Swan, 2015). It offers a great opportunity to facilitate the development of WM/SCPPS in several ways:

Blockchain data is time stamped, jointly validated and recorded by consensus nodes, and cannot be tampered with or falsified, which ensures the reliability of peer-to-peer exchange. Therefore, blockchains facilitate machine-to-machine communication and secure data transmission in IoT (Yu, et al., 2018), and what's more, make IoT cloud-centered architecture decentralized (Fernandez-Carames and Fraga-Lamas, 2018). Blockchains can be applied in registering and protecting intellectual property in digital manufacturing. As prosumers become a part in manufacturing, an efficient way to register and protect intellectual property is required. For example, in 3D printing industry, digital models of products are easy to be copied and reproduced by users (Holland, et al., 2017). Conversely, companies that produce varied no-identical products need new technical support to achieve full lifecycle tracking.

4.8. Digital twin

The first definition of the concept of digital twin (DT) was put forward by Michael Grieves in an industry presentation on product lifecycle management (PLM) in 2002 (Kritzinger, et al., 2018). Although the DT has a history of nearly 20 years and there is still no unified definition, it has been widely studied and applied in academia and industry. However, the DT is generally considered to be an integrated digital representation of individual products, which presents the properties, conditions and behaviors of real-life objects with the assistance of models and data (Haag and Anderl, 2018). DT has potential application value in many aspects, such as analysis and evaluation, predictive diagnosis and performance optimization, showing its superiority over traditional solutions.

The core of Industry 4.0 is CPS, and the main challenge it faces is to connect physical space and virtual space. The emergence of DT provides exciting possibilities for real-time simulation of the entire product lifecycle. Through the interaction and collaboration of virtual model and physical object, the virtual model can be synchronized and optimized with the physical object, and the physical object can be dynamically adjusted according to the direct instructions of the virtual model. Therefore, DT is also regarded as an important driving force for the realization of the smart manufacturing paradigm (Tao, et al., 2018).

4.9. Cobots

Industry 5.0 will completely change the definition of the word "robot". A robot is not only a programmable machine that can perform repetitive tasks, but will also become an ideal work and life companion for humans in some cases. Industry 5.0 will introduce the next generation of robots, commonly known as collaborative robots (cobots), which already know or can learn what to do soon, thus providing a human touch for the production of robots (Michaelis, et al., 2020).

Human-machine smart collaboration is one of the most distinguishing features of the Industry 5.0 era, in which cobots play a pivotal role. Humans and machines are no longer a competitive relationship, but a cooperative relationship (Nahavandi, 2019). Evolving from robots, cobots are a subdivision of robots that represent a breakthrough technology designed to enable high-level (e.g., collaborative) interactions between workers and machines, with the ability to be deployed flexibly in industries such as manufacturing (Michaelis, et al., 2020). Just as today's new generation has inevitably more interaction with smartphones, which they see as part of their lives, future human-robot interactions may be similar to today's human-smartphone interactions, and it seems that human-robot cooperation will be an important part of future sociological research (Demir, et al., 2019).

Although this study emphasizes the enabling technologies as discussed above, other technologies such as cloud and CPS are required too. As emerging edge/fog has limitations in data storage and computing power, edge/fog and cloud are likely to coexist and be complementary with each other to fulfill tasks (Pan and McElhannon, 2018). Their integration has the combined advantages of real-time, energy saving and security from fog and high computing power and large volume data storage capacity from cloud (Jing and Yao, 2019; Hashem, et al., 2015), thus resulting in more effective big data processing capabilities for manufacturing (Georgakopoulos, et al., 2016).

5. Towards Industrial Metaverse for Industry / Society 5.0

As shown in Fig.7, the blockchainized SCPS includes three subparts: blockchainized IoT/blockchain-based IoT (Ali, et al., 2018) or called IoTChain (Alphand, et al., 2018), blockchain-based IoP/blockchainized IoP or blockchainized Internet of Minds (Wang, et al., 2018), and blockchain-based cloud/ blockchainized IoS, resulting in such a socio-economic environment that allows a decentralized network of economic agents to agree about the true state of shared data, and resources can be organized or reorganized dynamically for production. As such, blockchains are not only used for transactions, but also used as a ledger or a registry and inventory management system for tracking, recording and monitoring all assets across the manufacturing value chain. Table I shows what value blockchains add to the three subsystems of SCPPS.

Table 1 Blockchains adding value to the SCPPS

Subsystem	Value added
Social	Decentralized transactions; Privacy protection; Crowdsourcing/Crowdfunding enabled; Trust improved; Time and costs reduced; Individually tailored customer experiences.
Cyber	Data integrity & Authenticity; Security; Supply chain auditing; Visibility/Transparency/Provenance improved; Piracy/Intellectual property protection;
Physical	Distributed/Decentralized decision-making; Automation enabled by smart contracts; Safety/Reliability enabled; Assets traced

As illustrated in Fig. 3, along with the Internet evolution from Industry 3.0 to Industry 5.0, we shift from the computer integrated manufacturing (CIM) that intends to integrate data scattered in various enterprise application silos during the PC era, to networked manufacturing integrating all data in a central database, to service-oriented cloud manufacturing integrating all data at the cloud, and to human-computer-service-thing integrated manufacturing (HCSTIM) decentralizing all or part of cloud data to the edge (or fog) (Yao, et al., 2019), which actually results in a distributed blockchainized SCPPS, where each smart device has its role and acts autonomously, and towards Industrial Metaverse, or metamanufacturing.

As shown in Fig.9, machine intelligence (especially for the production line) due to technology advances has undergone profound changes from the naked machine without intelligence to the autonomous one of high intelligence, that is, from the past focusing on liberating workers' physical labor to the current focusing on liberating workers' mental labor, resulting in the so-called Operator 1.0 - Operator 4.0 (Romero, et al., 2016; Romero, et al., 2016)) and toward Operator 5.0 featured by the division of human-machine labor: monotonous, repetitive, non-ergonomic and less innovation tasks done by machines, and innovative, research and artistic tasks by humans with the cooperation of cobots. Meanwhile, enterprise innovation gradually moves from closed to open, embedded and global (Zhang and Yao, 2016), and design goes from linear to competitive, networking and collaborative (Świątek, 2018). And design and innovation will meet at Industrial Metaverse in the name of Metadesign and Global Innovation respectively. Thus, operators (producers) is gradually eliminated from the production line - the so called human-in-the loop (HiL), and gradually entering in the cyberspace - the so called human-on-the-Loop (HoL) and even in the social space - the so called human-out-of-the-Loop (HofL), while the stakeholders such as consumers and ex-enterprise innovators, in the reverse direction, gradually enter an enterprise from HofL to HoL and toward HiL. Although machines (production lines) are of high of autonomy in Industry 4.0/5.0, in case of no HiL, there exist still humans in SCPPS, either in HoL or in HofL as shown in Fig. 6. In fact, the labor force shift from HiL to HoL to HofL just as from the primary industry (agriculture) to the secondary and service industries. For example, there will be Operator 5.0 in the loop (HiL) for interacting and collaborating with cobots in Industry 5.0. Besides, consumers/users participate the manufacturing for individual experiences.

A similar concept to Industry 4.0 is the Industrial Internet, which can be viewed as the result of "Industrial Revolution +Internet". Now the Internet is moving to the Metaverse (Park and Kim, 2022), so we have "Industrial Internet + Metaverse = Industrial Metaverse", as shown in Fig.10. Before the emergence of the Internet, there existed "information islands" in manufacturing, and machines were not connected together. In the new industrial revolution, the rapid development and widespread use of the Internet has given rise to the Industrial Internet, i.e., IIoT, which is an interconnection of things, realizing the interconnection of humans, machines, things and the environment. Now with the rise of the Metaverse, the Industrial Internet will further develop into the Industrial Metaverse, where the real world and the virtual world (Metaverse) will have no obvious boundaries, influencing and evolving each other. The real world is connected by IoP and IoT, while the virtual world is connected by IoS and IoCK. That to say, Industrial Metaverse is connected by IoP, IoT, IoS and IoCK as the wisdom manufacturing is.

Metaverse is a much larger and more complex concept than DT, and it is generally believed that DT is a subset of Metaverse or one of the enabling technologies for Metaverse. Although Metaverse emerged about 10 years before the DT, its related technology system is still very incomplete and needs to be studied more deeply by academia and industry. The DT originated in the industrialization of complex product development and is moving toward socialization and globalization, while Metaverse originated in the gaming and entertainment industry and is expanding from globalization to socialization and industrialization. A schematic diagram of the evolutionary route of Metaverse and DT is shown in Fig.11.

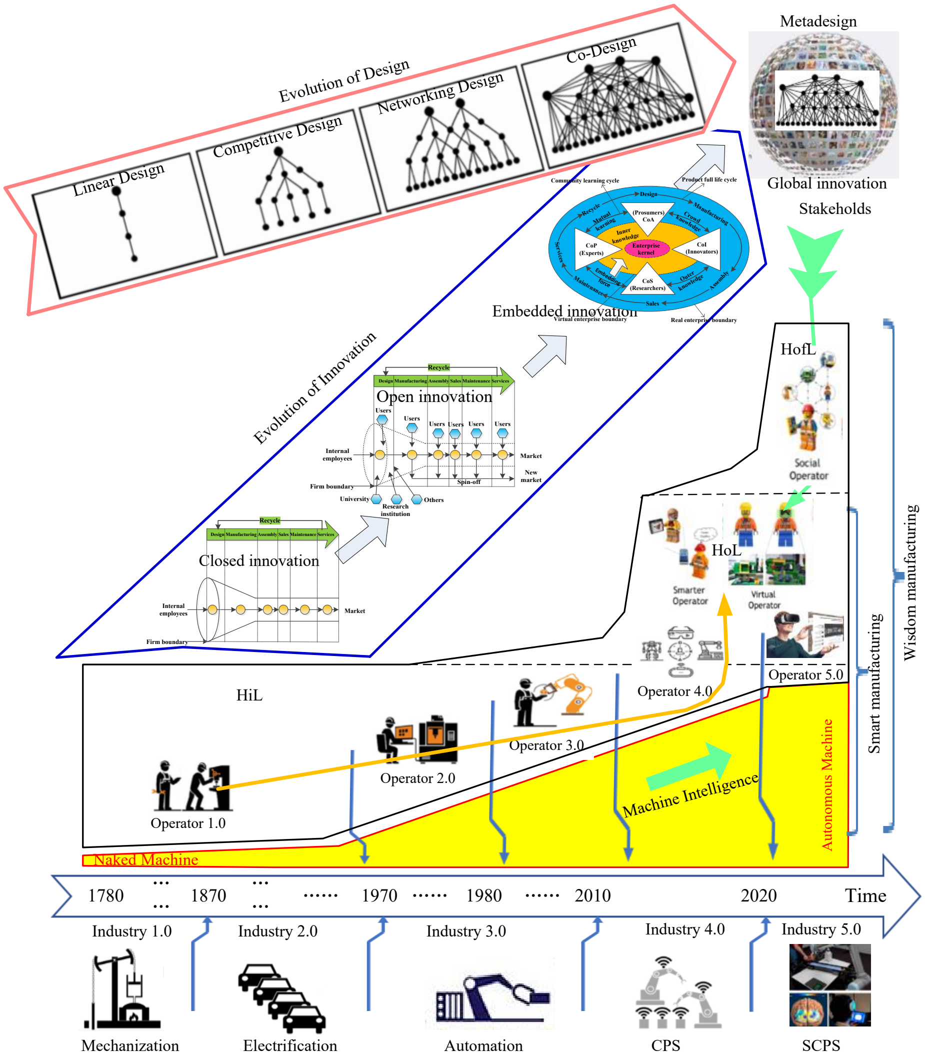


Fig. 9 Towards Industrial Metaverse for Industry/Society 5.0

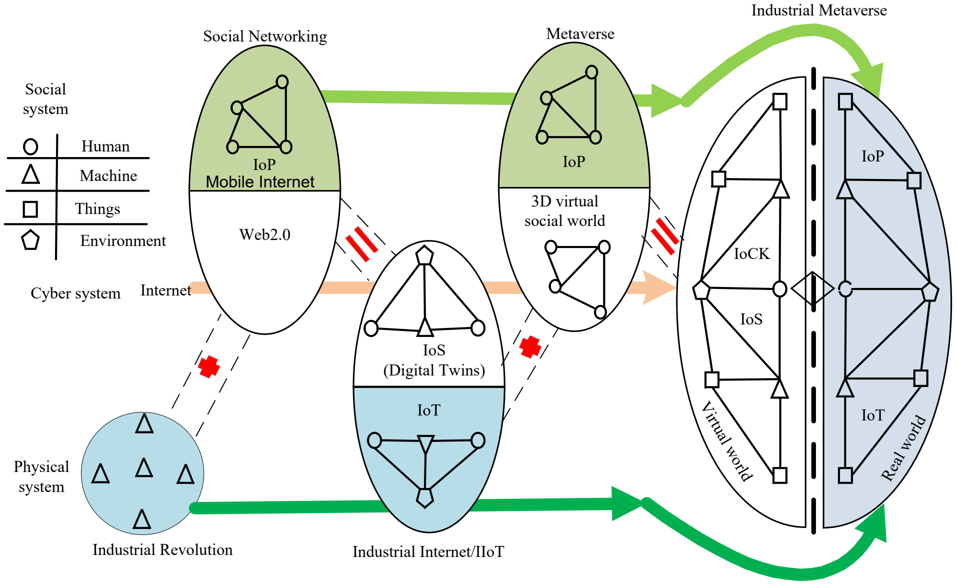


Fig.10 From Industrial Revolution to Industrial Internet to Industrial Metaverse

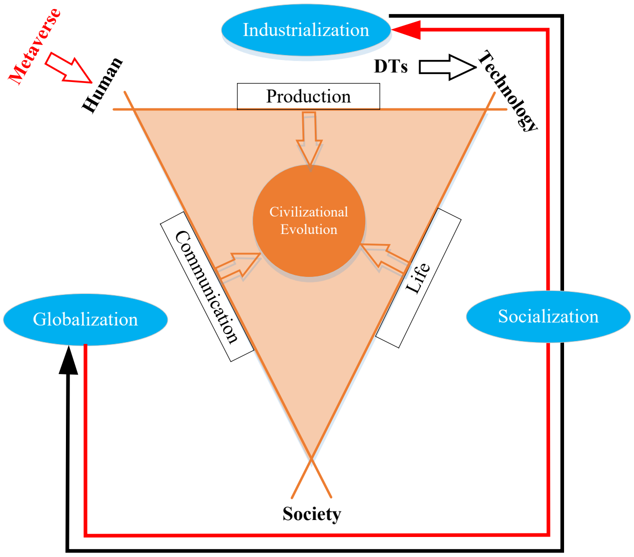


Fig.11 A schematic diagram of the evolutionary route of metaverse and DT

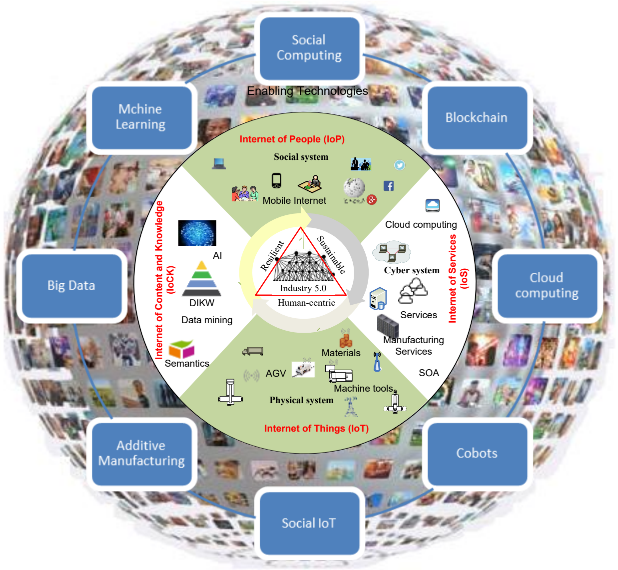


Fig.12 Enhancing wisdom manufacturing as Industrial Metaverse for Industry/Society 5.0

Although both Metaverse and DT are concerned with the connection and interaction between the real world and the virtual world, the essential difference between the two is that they have completely different starting points. Metaverse is directly oriented to humans, while the DT is first oriented to technology (things). However, both complement each other.

As such, wisdom manufacturing is enhanced as Industrial Metaverse (Metamanufacturing), still in the form of SCPPS, to integrate all stakeholders (including producers and consumers, ex-enterprise innovators and others), machines (including machine tools, and robots, cobot and other devices), and things (such as workpieces and materials) together with extensive participation in participatory design and building advantageous value chain (Świątek, 2018), as well as Global Innovation and supporting the growing diversity and individual needs of human beings in the future by absorbing the widest range of innovative and creative wisdom of the world's most talented people. Therefore, Industrial Metaverse will provide a vision of Industry 5.0 that aims beyond efficiency and productivity as the sole goals and reinforces the role and the contribution of industry to society, and enables smart, resilient, sustainable, and human-centric solutions to satisfy experience-driven individual needs, as shown in Fig.12.

6. Conclusion

For the purpose of developing Industry 5.0 manufacturing to meet economic, environmental, and social challenges, a socio-technical revolution based on SCPS has been addressed. We have developed a socio-technically enhanced wisdom manufacturing architecture and a blockchainized SCPS-based decentralized framework, and discussed Industry 5.0 key enabling technologies and the roadmap to blockchainized value-added SCPS-based Industrial Metaverse for Industry 5.0.

Such a proposed architecture/framework extends CPS-based Industry 4.0 to SCPS-based Industry 5.0 to integrate stakeholders' ideas, thoughts and innovations for mass personalization, and the resultant Industrial Metaverse can provide products and services that satisfy experience-driven individual needs. However, Industrial Metaverse is in the early stage of concept formation, and there are many details that need to be further studied.

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