DIKW Upward Enabling Manufacturing from Digitalization in Industry 3.0 to Wisdom in Industry 4.0

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***Abstract*—The upward progress in Data-Information-Knowledge-Wisdom (DIKW) has advanced manufacturing from digitalization to networking in Industry 3.0, and to intelligence and even wisdom in Industry 4.0, which reveals the inevitable trend of manufacturing evolution from "Computer Plus" to "Internet Plus" to "Knowledge Plus" and towards "Wisdom Plus". Wisdom manufacturing is the further development of intelligent/smart manufacturing in the form of social-cyber-physical system by integrating Internet of Things, Internet of Services, Internet by and for People, and Internet of Contents and Knowledge in manufacturing as a whole.**

Keywords—wisdom manufacturing, industry 4.0, evolution of manufacturing paradigm

I. Introduction

Manufacturing had undergone dramatic and fundamental transformations from mechanization to electrification and automation along with Industry 1.0 to 2.0 and 3.0, and nowadays is facing more transformation towards smartness and even wisdom in Industry 4.0 [1]. Such transformative enablers are information and communication technologies (ICT)/AI technologies, to which DIKW are central. As such, there is a need to address DIKW roles in manufacturing paradigm shifting from Industry 3.0 to 4.0.

II. Manufacturing Paradigm Shifts from Industry 3.0 to 4.0

Advances in ICT/AI progress manufacturing from Computerized Digitalization (Computer+), Network Informatization (Network/Internet+), and Knowledge-based Intelligence/Data-driven Smartness (Knowledge/AI+) toward Wisdom+, as shown in Figure 1.

In Industry 3.0 (I3.0), manufacturing was digitalized by computers, and then networked by computer networks/Intranet [1], thus resulting in vertical integration within the enterprise among its all levels such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES) and control by computer networking at first, and later horizontal integration between different enterprises such as suppliers and other value network partners across company borders along with the emergence and development of Internet. In Industry 4.0 (I4.0), there is one more integration called "end-to-end" based on both vertical and horizontal integrations [2], which integrates for closing gaps between the customer and product design and manufacturing, especially for customized/personalized products across the entire product lifecycle, resulting in the so-called cyber-physical production system (CPPS), and even social-cyber-physical production system (SCPPS), with a loose coupled service-oriented architecture instead of the tight coupled hierarchical architecture in I3.0.

A. Manufacturing digitalization and networked in industry 3.0

With a focus on DBMS-based structured contents in I3.0 era, manufacturing was digitalized by computers and then networked by the computer network/the Internet. The former is the result of "Computer Plus", and the latter is that of "Network/Internet Plus".

1) Manufacturing digitalized by computers: Digital manufacturing began at around the birth of the electronic computer in 1946, especially at that of personal computers. Later, such computerization in manufacturing resulted in the so called computer aided technologies (CAX) such as CAD, CAM, CAE, and CAPP. Manufacturing in such an age of "Computer Plus" (around 1940-70s) was characterized by computerized digitalization.

2) Manufacturing networked by computer network/Internet: In 1980s and later on, computer integrated manufacturing (CIM) was used to integrate CAx and MRP/MRPII by computer networks. In particular, globally integrated manufacturing was enabled with the emergence of Internet beginning at the 1990s, and management information systems such as ERP and CRM (Customer Relationship Management) were emerging. As a result, in the age of "Network/Internet Plus" (1980s-2000s), manufacturing was characterized by networking/ internetworking, and MES emerged as a translation layer between ERP and the control layers in the so-called enterprise integration. Although knowledge-based intelligent manufacturing (IM) was also born at this age, it

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existed as "intelligent island" and was dominated by more popular CIM and other related manufacturing models such as lean production (LP) and agile manufacturing (AM) [3].

Vertical integration within an enterprise began at the emergence of CIM, and horizontal integration between different enterprises began at the emergence of Internet with focus on IT (information technology) such as ERP and CRM. And there was a gap between IT and OT (operational Technology) among enterprises.

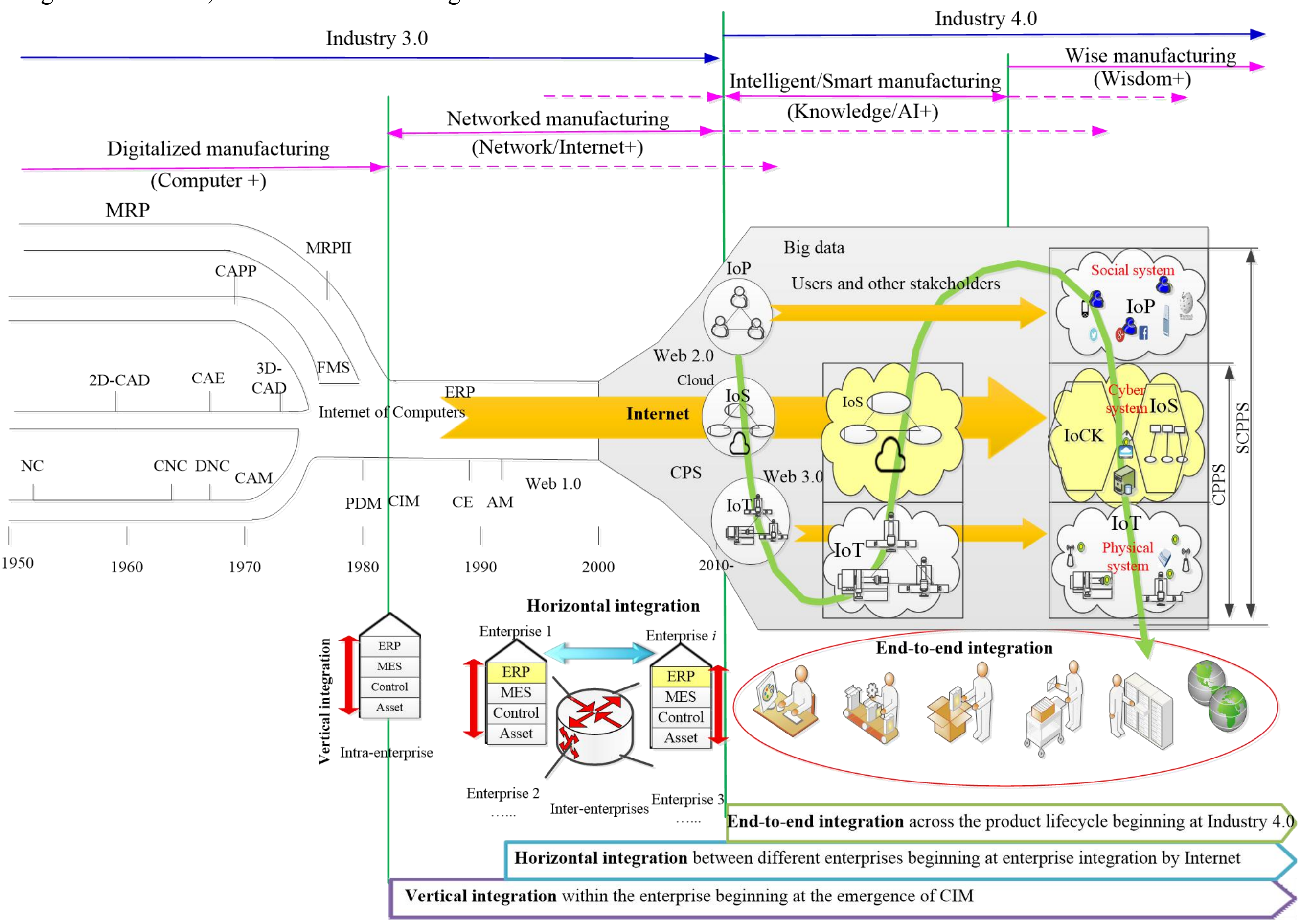


Fig. 1. Manufacturing paradigm evolution from Industry 3.0 to 4.0

B. *Manufacturing intelligence and wisdom in Industry 4.0*

With a focus on unstructured contents (big data) in I4.0 era, new-generation IM has been emerging with vertical and horizontal integrations as well as end-to-end integration [2, 4], and meanwhile traditional IM is revived especially after the emergence of Knowledge Graph.

1) Intelligent/smart manufacturing driven by knowledge/big data: Along with the development of knowledge-based and multi-agents based manufacturing systems, the introduction of new-generation ICT/AI such as the Internet of Things (IoT), the Internet of Services (IoS), cyber-physical systems (CPS), cloud, big data, and deep learning in manufacturing, has resulted in new-generation IM, called smart manufacturing (SM) or CPPS, which is be viewed as the result of "New-generation ICT/AI Plus"[1] as the extension of "Knowledge Plus". The new-generation ICT/AI bridges the gap between IT and OT, and enalbes the end-to-end integration across the product lifecycle along with the existing vertical and horizontal integrations. Although there are different emerging SM models such as the Smart Factory based on IoT, service-oriented cloud manufacturing based on IoS/cloud, and proactive manufacturing driven by big-data, these SM models as well as traditional knowledge-based IM can enclosed under the umbrella of so-called wisdom/wise manufacturing (WM) [5] as stated below.

2) Wise manufacturing driven by wisdom: WM was firstly issued in 2014 by integrating IoT, IoS, IbfP (Internet by and for People)/ IoP (Internet of People), and IoCK (Internet of Contents and Knowledge) in manufacturing as a whole [6], and then was further elaborated and studied as a socio-technical system [7], or a socio-CPPS from the perspective of organization semiotics [8] or from the perspective of future networked society consisting of agents and humans [9], big data [10], new-generation ICT/AI [11], sustainable development [12], and inclusive growth [13]. In the end, WM system theory and technology [14] is formed in the form of social-cyber-physical system with the characteristics of sustainability and inclusiveness [13], consisting of 3 subsystems: physical, cyber and social, or of 6 organization semiotics levels: physical, empiric, syntactic, semantic, pragmatic, and social, as shown in Figure 2. In fact, such an inclusive WM system becomes a socio-economic-techno-production system [13], turning manufacturing from environment-oriented sustainable to people-oriented inclusive.

III. DIKW Upward Progressing Manufacturing

As revealed in Figure 1, manufacturing evolves along with "Computer +", "Internet +", "Knowledge +" and "Wisdom +". As a result, digitalized, networked, intelligent, and wise manufacturing paradigms are formed, which are upward enabled by DIKW hierarchical levels - Data, Information, knowledge and Wisdom, respectively, as shown in Figure 3. In a way, IoCK can be viewed as DIKW, which links data, information, knowledge and wisdom. As a result, WM not only can be viewed as a general framework for smart manufacturing models in the new industrial revolution [3], but also have the potential to be generalized as a framework for Society 5.0 proposed by Japan [15].

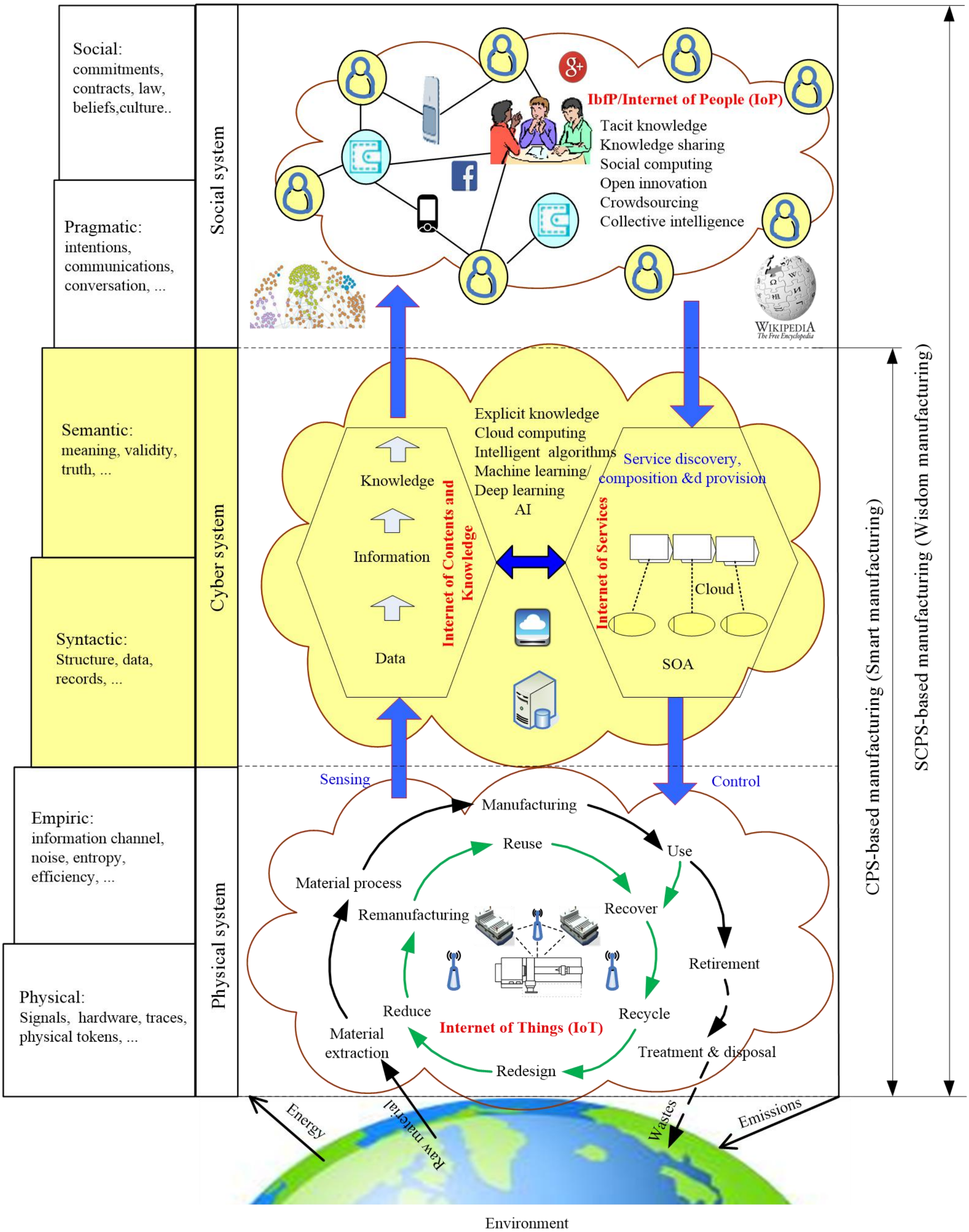


Fig. 2. Framework for human-oriented inclusive wisdom manufacturing

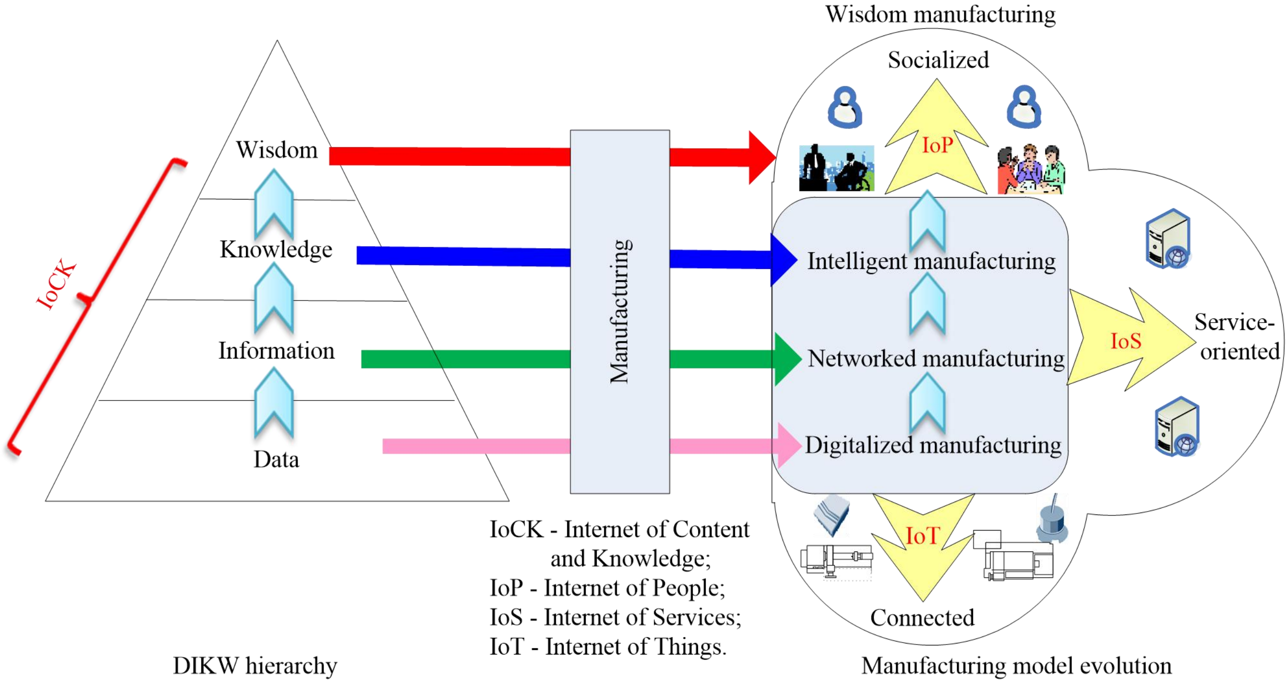


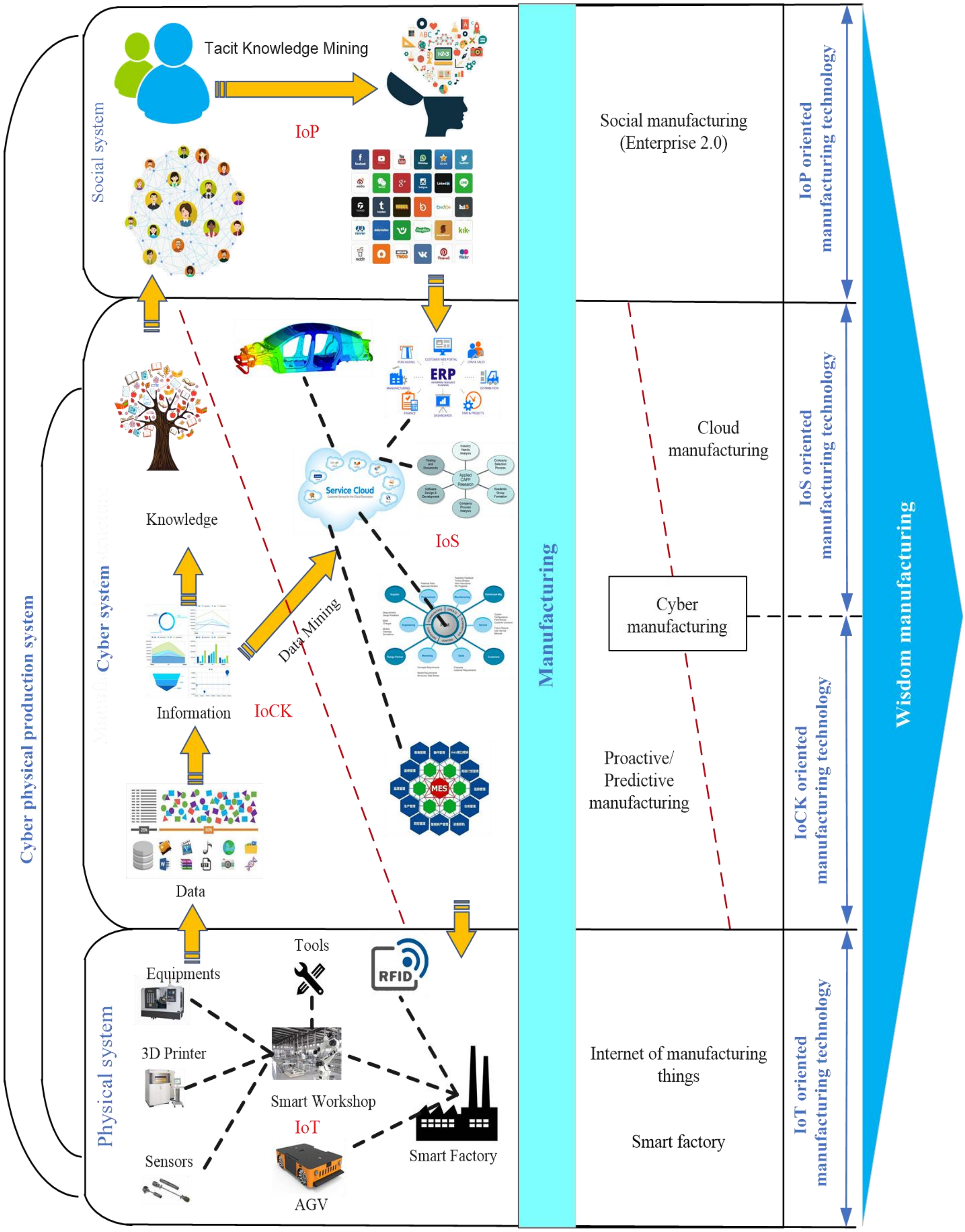
Fig. 3. Manufacturing evolution from the perspectives of the DIKW hierarchy

As shown in Figure 2, compared with intelligent manufacturing, wisdom manufacturing places more emphasis on collective intelligence, knowledge use and human initiative, especially knowledge acquisition, knowledge accumulation, knowledge sharing, knowledge utilization and knowledge innovation with the help of social software and the IoP, and pays more attention to the interactivity, personalization and innovation of customer participation. From digitalized manufacturing to wisdom manufacturing, corresponding to the different levels of DIKW, data is the foundation, from which useful information is obtained to achieve knowledge utilization, knowledge dissemination and knowledge sharing in the IoP, and then integrating the hidden tacit knowledge in the IoS to achieve precise control and wisdom decision-making in the manufacturing process. Efficient utilization of knowledge and knowledge innovation are the key elements in the process of realizing wisdom manufacturing.

The innovation methods in manufacturing have evolved from closed innovation/Innovation 1.0 and open innovation (Innovation 2.0) to the emerging embedded innovation (Innovation 3.0/Innovation 4.0). Such innovation evolution from closed in the past to open and even embedded today, indicates that the boundaries of an enterprise have become more flexible, allowing internal resources and external stakeholders to collaborate and innovate throughout the entire product life cycle [16]. Open innovation allows stakeholders to participate in the process of product innovation and development. Thus consumers/users become co-designers of products. There is no absolute boundary between users and product designers, and they promote each other to satisfy consumer's individual needs. Knowledge innovation plays an important role in the DIKW process, i.e., in the process of obtaining the final wisdom decision from raw data. In the future, as more and more innovation interest communities, e.g., communities of affinity, communities of practice, communities of interest and communities of science, are established, they will surely provide a constant source of innovation, technology support for wisdom manufacturing.

As a social-cyber-physical production system, wisdom manufacturing is a further extension of the existing intelligent/smart manufacturing or CPPS, emphasizing on collective intelligence and open innovation with user participation, forming human-oriented, user-centered socio-technical system to meet the needs of the future society (Society 5.0) for the demand for smart products and services.

Wisdom manufacturing and its subsystems are shown in Figure 4, which are mainly composed of four pillar manufacturing technologies, namely IoT-oriented, IoCK-oriented, IbfP/IoP-oriented, and IoS-oriented. The whole wisdom manufacturing system can be considered as the "four networks" (IoT, IoCK, IbfP and IoS) plus manufacturing, in which "IoT + manufacturing" forms the Internet of manufacturing things or so-called smart factory; "IoCK + manufacturing" generates emerging data-driven smart manufacturing such as proactive/predictive manufacturing, traditional knowledge–driven intelligent manufacturing, and even linked data- and knowledge- driven smart manufacturing; "IbfP/IoP + manufacturing" forms social manufacturing or Enterprise 2.0; and "IoS + manufacturing" gives birth to the service-oriented manufacturing represented by cloud manufacturing. Similarly, there are hybrid combinations with 2 or more of the "four networks". For example, "IoT + IoCK + IoS + manufacturing" forms the cyber-physical production system. As such, both emerging smart manufacturing and existing traditional intelligent manufacturing can be covered under the umbrella of wisdom manufacturing.



IoCK - Internet of Content and Knowledge; IoP - Internet of People; IoS - Internet of Services; IoT - Internet of Things.

Fig. 4. Wisdom manufacturing and its technology system

IV. Conclusion

This study discusses the role of DIKW in the progress of manufacturing from digitalization in Industry 3.0 to wisdom Industry 4.0. In fact, such manufacturing transformation progress covers from digitalization to networking and then to intelligence and wisdom, and both emerging smart manufacturing and existing traditional intelligent manufacturing can be covered under the umbrella of wisdom manufacturing.

The wisdom manufacturing in the form of social-cyber-physical system consists of 3 subsystems with 6 organization semiotics levels, which can be viewed as the further development of IM/SM driven by knowledge/wisdom and big data, and it covers four pillar manufacturing technologies based on IoT, IoS, IoCK, and IbfP/IoP, respectively. While sustainable manufacturing idea with 6R (Reuse, Recover, Recycle, Redesign, Reduce, Remanufacturing) as well as inclusive growth is covered, wisdom manufacturing pays more attention to the interaction of data, information and knowledge, social value as well as collective intelligence, resulting in human-oriented inclusive manufacturing with the consideration of both the technological and human factors in production and service, which can better meet the future society (Society 5.0) need of manufacturing innovation and inclusiveness.

There is no doubt that DIKW promote the evolution of manufacturing. However, such socially inclusive wisdom manufacturing is still in the initial step of system exploration, and its contents need to be further established and examined in more detail. This paper only addresses the role of DIKW in wisdom manufacturing from a macro perspective, and its specific contents involved in the sociotechnical system need to be further enriched and researched.

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