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Research on the General Architecture of Intelligent Manufacturing

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Abstract: Intelligent manufacturing is an evolving system that includes the theories, methods, technologies, and applications involved in the entire life cycles of products, manufacturing processes, and services. Considering emerging new technologies, concepts, and models in the field of intelligent manufacturing, a system structure needs to be proposed and summarized to guide the implementation of intelligent manufacturing. This study constructs a system structure for intelligent manufacturing in China from three dimensions: the value, technical, and organization dimensions; comparisons are also drawn with other system architectures related to intelligent manufacturing in the United States, Germany, and Japan. The technical dimension reflects that China's intelligent manufacturing should focus on the integration of industrialization and informatization, the value dimension reflects that the main body of China's intelligent manufacturing comprises manufacturing activities, and the organization dimension emphasizes that China's intelligent manufacturing should be people-oriented.
Keywords: intelligent manufacturing; general architecture; intelligent transformation; optimization and upgrade

1 Introduction

With the increasing integration of information technology and manufacturing in recent years, intelligent manufacturing is rapidly commanding success globally in the present new round of the scientific and technological revolution as well as in industrial transformation. To gain a competitive advantage in intelligent manufacturing, several intelligent-manufacturing system architectures have been proposed by researchers in the industry and academia in different countries. These system architectures provide a reference for future strategic planning in intelligent manufacturing and guide the global standardization of intelligent manufacturing initiatives. Currently, the exploration and analysis of the general architecture of intelligent manufacturing in China is a critical and urgent task that promotes the national development of intelligent manufacturing methods.

2 Basic idea of the general architecture of intelligent manufacturing

Intelligent manufacturing is a broad concept comprising the entirety of the product, manufacturing, and service life cycles [1]. The general architecture of intelligent manufacturing (also known as the intelligent manufacturing system architecture or the reference architecture of the intelligent manufacturing system) is a mapping of all the relevant elements and relationships between the elements associated with intelligent manufacturing. It provides a conceptual and modular understanding of the different activities involved in intelligent manufacturing [2].

The design of the general architecture of intelligent manufacturing plays an important role at multiple levels. From a microscale perspective, its general architecture can provide a

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framework for construction, development, integration, and operation in intelligent manufacturing practices. From a mesoscale perspective, it provides technical guidance to enterprises for implementing intelligent manufacturing. From a macroscale perspective, it offers a high-level design model at a national scale for planning and driving the intelligent transformation of manufacturing [3].

3 Dimensions of the general architecture of intelligent manufacturing

In this study, the general architecture of intelligent manufacturing is proposed on the basis of three dimensions, namely value, technology, and organization (as shown in Fig. 1).

3.1 Technology dimension

The technological evolution dimension focuses on the integration of informatization and industrialization. In this dimension, intelligent manufacturing can be categorized into three paradigms: digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing (as shown in Fig. 2). These three paradigms are interrelated and the technological evolution occurs iteratively from one step to the next.

Digital manufacturing is the foundation of intelligent manufacturing. It is a key component in all three paradigms and keeps evolving and developing over time. Smart manufacturing elevates digital manufacturing to the next level and aims to optimize the value chain by promoting industrial "Internet + manufacturing" practices in the relevant industry sectors. New-generation intelligent manufacturing is proposed based on these first two paradigms, in which the manufacturing process is endowed with true intelligence by integrating advanced manufacturing technologies with artificial intelligence.

3.1.1 Digital manufacturing

Digital manufacturing, as shown in Fig. 2(a), is an integrated approach that combines digital and manufacturing technologies. This approach emerged after digital technologies became popular and were widely used in different applications. Digital manufacturing can enable digital design, simulation, and computer-integrated manufacturing processes, thereby realizing the integration and collaboration of production and management in an enterprise. By integrating the computer systems with the production systems in a factory, digital manufacturing can improve product design, manufacturing quality, and labor productivity, as well as shorten product-development life cycles, reduce costs, and improve energy efficiency.

Digital manufacturing exhibits the following characteristics:

(1) Digital manufacturing enables the digital expression of different subjects in the manufacturing process. Specifically, this includes the digitization of the product and technology; the manufacturing equipment or facility; relevant objects including materials, components, processed parts, and molds, fixtures, or tools; and human labor.

(2) Exchanging and interconnection of data. This involves the establishment of networked communication systems, the standardization of heterogeneous data formats from different sources, and the standardization of the specific meanings for the terms used in the data.

(3) Integration of information. Production and operation data are integrated with an information management system to use these data for realizing a collaborative and visual management of the different aspects of the entire manufacturing process.

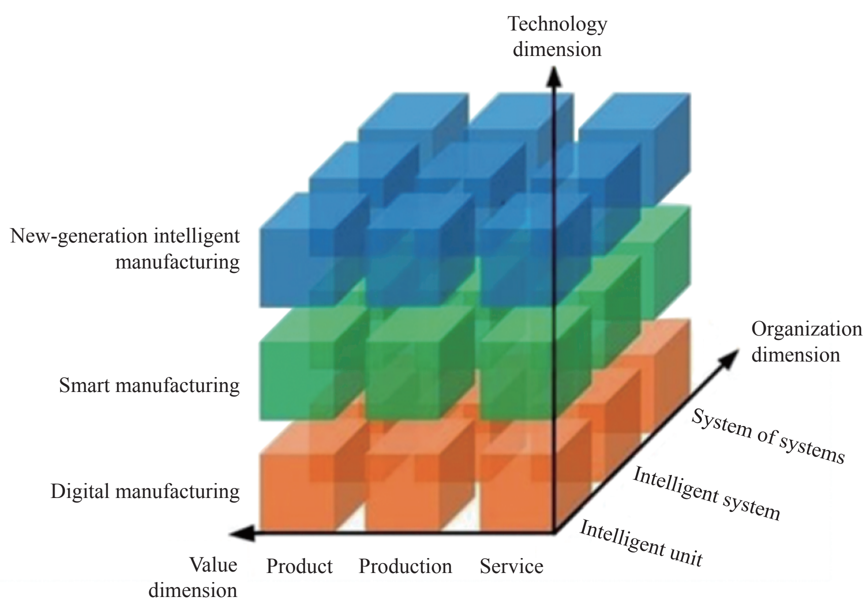

Fig. 1. General architecture of intelligent manufacturing.

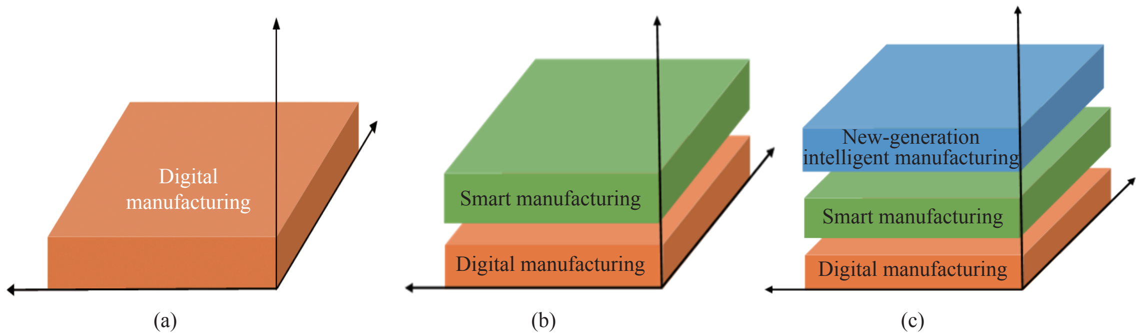

Fig. 2. Schematic diagram showing a breakdown of the general architecture of intelligent manufacturing in the technology dimension.

3.1.2 Smart manufacturing

The smart manufacturing scheme shown in Fig. 2(b) is established on the basis of digital manufacturing. With the wide application of network technologies, information can now be exchanged between enterprises, including both the production and demand sides. This allows for the integration of supply–demand information between enterprises and customers, and enables a better synergy between the upstream and downstream supply chains of enterprises. Ultimately, such practices change the business models of corporations, optimize the entire industrial chain, and provide the quick, high-quality, and low-cost products and services needed by the market.

Smart manufacturing exhibits the following characteristics:

(1) Smart manufacturing enables thorough communication with the customer. This allows the enterprise to develop a better understanding of customer requirements and therefore go from a product-centered to a customer-centered operation mode.

(2) Smart manufacturing helps realize a synergy between different enterprises in the entire industry chain. Specifically, this includes the synergy of data, resources, and workflow between different enterprises. Such synergy can optimize the allocation of social resources.

(3) Smart manufacturing helps extend the production chain of the enterprise to cover not only products but also services. By combining long-range operation and maintenance modes, the enterprise can now provide customers with more value-added services, which helps the company transform from a production-oriented business to a production service-oriented business.

3.1.3 New-generation intelligent manufacturing

The new-generation intelligent manufacturing scheme shown in Fig. 2(c) is developed recently as a result of the integration of artificial intelligence and manufacturing technologies. The breakthroughs in new-generation intelligent manufacturing technologies have spawned many intelligent applications, such as multimedia intelligence, cross-media intelligence, group intelligence, human–machine hybrid enhancement intelligence, big data intelligence, and autonomous intelligent systems. These fields provide new horizons for development in the manufacturing industry [4].

New-generation intelligent manufacturing can enable automated manufacturing/services based on manufacturing knowledge. By implementing deep learning, migration learning, and enhanced learning technologies, manufacturing data and information can now be "automatically" converted to knowledge. In other words, the manufacturing industry is endowed with the capability to "learn," which will bring revolutionary changes to the efficiency of the generation, accumulation, application, and inheritance of manufacturing knowledge. Such practices will unleash the potential of human intelligence in the manufacturing industry and significantly improve innovation and service capabilities. With this transformation in the generation of manufacturing knowledge, new-generation intelligent manufacturing will become a new model and eventually a true intelligent-manufacturing technique with the integration of artificial intelligence technology.

3.2 Value dimension

The value dimension is a manufacturing-oriented value-realization dimension. Intelligent manufacturing is primarily composed of intelligent products, intelligent production, and intelligent services. Specifically, intelligent products, intelligent production, and the intelligent service-oriented transformation of industry modes are the main subject, activity, and theme in intelligent manufacturing. The value realization of intelligent manufacturing is primarily reflected in three aspects, namely products, production, and services, as shown in Fig. 3.

(1) Intelligent products: Intelligent products include both the equipment used for intelligent production as well as the various output products. Owing to intelligent manufacturing technology, these products exhibit improved functionality and better performance, which grants them greater added value and stronger competitiveness in the market.

(2) Intelligent production: Intelligent production covers different aspects associated with the manufacturing process, such as the design, manufacturing, and management of the product. The integration of manufacturing and information technologies

can provide an overall enhancement to the level of design, production, and management of products. These merits can also significantly improve labor productivity.

(3) Intelligent services: Intelligent services include a variety of customer-centered services throughout the life cycle of the product. The intelligentization of product services will greatly promote the development of different production methods, such as personalized customization, extending the development of service-oriented manufacturing and producer services industries and causing a profound transformation to the production modes and characteristics of the manufacturing industry.

In addition, system integration is the key for the value realization of intelligent manufacturing. The core of integration is to resolve the interconnections and interoperability issues between the different systems and consequently upgrade from local to global optimizations. Ultimately, system integration can improve the eco-efficiency of the entire manufacturing industry associated with equipment, production, services, market, and management.

3.3 Organization dimension

This is a people-oriented organized system dimension. Intelligent manufacturing is a broad system that exhibits an unprecedented characteristic of "large-scale integration" of systems both internally and externally. From the organization dimensions perspective, intelligent manufacturing is primarily reflected in three layers, namely intelligent unit, intelligent system, and system of systems (as shown in Fig. 4).

(1) Intelligent units: The intelligent unit is the smallest unit that can realize the function of intelligent manufacturing, such as a single component or a product. Using a combination of hardware and software, intelligent units can be integrated to realize a closed data loop of sensing–analysis–decision making–execution.

(2) Intelligent systems: Intelligent system refers to the integration of multiple intelligent units that can achieve automatic data flow within a larger and broader scope. This approach can increase the breadth, precision, and depth of allocation of manufacturing resources in multiple forms, such as manufacturing equipment, production units, production lines, workshops, and enterprises.

(3) System of systems: The system of systems is the carefully arranged integration of multiple intelligent systems established through the industrial Internet and intelligent cloud platforms. The system of systems enables horizontal, vertical, and end-to-end integrations across different systems and platforms, which contribute to developing an open, collaborative, and shared industrial ecosystem. A significant aspect of the system of systems is the "large-scale integration" within the manufacturing system itself. Specifically, the facilities and systems in the equipment layer, field layer, control layer, management layer, and enterprise layer of an enterprise are integrated. This is known as vertical integration. Another aspect in the system of systems is the integration, sharing, collaboration, and optimization between different enterprises, which are made possible through industrial intelligent networks and intelligent cloud platforms. This "large-scale integration" outside the manufacturing system is known as horizontal integration. In addition, the in-depth integration of manufacturing and financial industries as well as the upstream

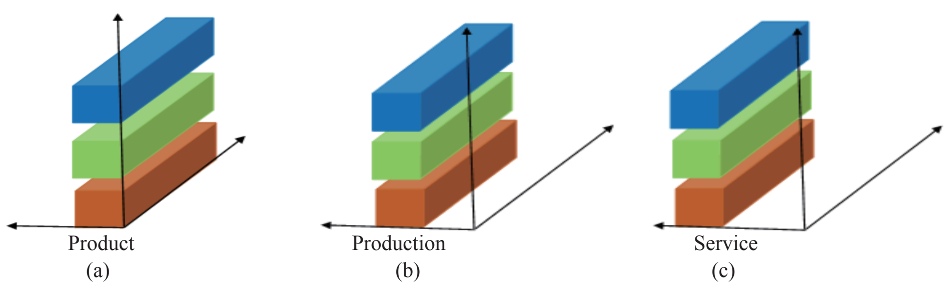

Fig. 3. Schematic diagram showing a breakdown of the general architecture of intelligent manufacturing in the value dimension.

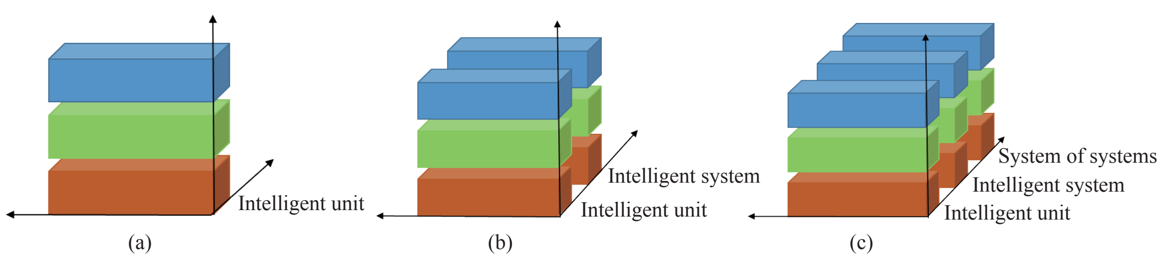

Fig. 4. Schematic diagram showing a breakdown of the general architecture of intelligent manufacturing in the organization dimension.

and downstream industries have shaped a new industry scenario featuring the joint development of service-oriented manufacturing and producer services industries.

4 Comparative analysis of the general architecture of intelligent manufacturing

During the development of intelligent manufacturing in recent years, many technical system architectures were proposed by research institutes from different countries [5]. For example, the Industrial Internet Consortium in the United States published "The Industrial Internet Reference Architecture (IIRA)"; the DKE German Commission for Electrical, Electronic & Information Technologies of the DIN and VDE issued the "Reference Architecture Model for Industry 4.0 (RAMI4.0)"; the Industrial Value Chain Initiative in Japan has published "Industrial Value Chain Reference Architecture (IVRA)"; and the National Intelligent Manufacturing Standard Office in China has issued "The General Architecture of Intelligent Manufacturing" [6]. Comparing these system reference architectures can provide a clear representation of the basic characteristics of the general architecture of intelligent manufacturing.

4.1 Comparison in the technology dimension

The technology dimension of the general architecture of intelligent manufacturing reflects the changes in intelligent manufacturing technology, which are focused on the integration of industrialization and informatization. It demonstrates the scalability of different technologies and is very similar to the IIRA. The IIRA is a system framework established in specific application areas that describes the practices, principles, time, and activities for the relevant interest groups [6]. This architecture provides a basic framework that can be expanded and used as a reference for establishing architectures in other fields. The General Architecture of Intelligent Manufacturing is also a general development architecture developed from a macroscale perspective. It exhibits a wide range of applicability and interoperability across different industries.

4.2 Comparison in the value dimension

The value dimension of intelligent manufacturing reflects the manufacturing-oriented form of value realization for intelligent manufacturing. Both the General Architecture of Intelligent Manufacturing and the RAMI4.0 [7] describe the entire life cycle of manufacturing products and their associated value chains. The core of the RAMI4.0 is intelligent manufacturing technology and intelligent manufacturing modes. The main objective here is to coherently link products, equipment, resources, and people together to drive data sharing across all segments, thereby realizing the digitization of the entire life cycle and the entire manufacturing process. The General Architecture of Intelligent Manufacturing is focused on the digitalization of the entire life cycle of the manufacturing value chain. In terms of strategic planning and sensitivity to the application of new technologies, the General Architecture of Intelligent Manufacturing provides a more comprehensive coverage of the paradigms for networked and intelligent development. Therefore, it is a more advanced architecture with a wider range of adaptabilities.

4.3 Comparison in the organization dimension

The organization dimension of intelligent manufacturing reflects the expansion of people-oriented intelligent-manufacturing organization systems. The organization dimension in the General Architecture of Intelligent Manufacturing involves lessons learnt from the industrial value chain in Japan [8] and the system architecture of intelligent manufacturing in China [9]. There are three layers proposed in the organization dimension in the General Architecture of Intelligent Manufacturing: intelligent units, intelligent systems, and system of systems. This aims to help enterprises build the most basic manufacturing unit, then realize intelligent workshops, intelligent factories, and intelligent enterprises step-by-step; eventually, intelligent enterprise clusters and regional clusters can be formed. These clusters can be further expanded to the entire country to benefit from the mutual development of large-, medium-, and small-sized enterprises; parallelly promote the digitalization, networking, and intelligentization of the manufacturing industry; and ultimately realize the overall transformation and upgrading of enterprises in the manufacturing industry.

In general, if the intelligent manufacturing reference architecture models proposed by the United States, Germany, and Japan mainly focus on the high-end industries and high-end links in manufacturing, then the General Architecture of Intelligent Manufacturing proposed in this study focuses on the overall planning for the transformation and upgrading of the entire manufacturing industry in China. In particular, this general architecture considers the unbalanced and inadequate development of the manufacturing industries in China and proposes three basic paradigms for iterative evolution, including digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing. It is emphasized in this architecture that the development of intelligent manufacturing industries in China must adhere to the principle of parallel advancement and integrated development. This strategy not only guides the transformation and upgrading of traditional manufacturing industries but also provides far-reaching planning guidance for the future development of the manufacturing industry and leading technologies [10]. The future development of the manufacturing industry will not only require realizing the digitization of products' life cycles and the entire manufacturing process, which can be considered as an Internet of Everything formed via end-to-end networking, but also achieving the intelligent development of the entire manufacturing industry under the guidance of a new generation of artificial intelligence technologies.

5 Conclusion

It has been clearly stated in the "China Manufacturing 2025" plan that the integration of next-generation information technologies and the manufacturing industry are the main theme, whereas promoting intelligent manufacturing is the main direction for future development. At this historical intersection of technology and industrial change as well as the national economic development transformation, it is critical to establish a technological route and strategy for the vigorous development of intelligent manufacturing in China. Such strategies should follow a different direction from what has been adopted by the developed countries of the world to accelerate the transformation of manufacturing intelligence in China and ultimately allow China to transform from a manufacturer of quantity to quality products.

With new technologies, ideas, and models that are continuously emerging in the field of intelligent manufacturing, it is necessary to summarize and develop a general architecture that can guide the government and enterprises to explore new technologies. By applying these new concepts and models, we can better exploit the opportunities at this historical intersection of the industrial and technological revolution to achieve an intelligent transformation and an optimization of the manufacturing industry in China over a shorter time and with better quality. The proposal of the General Architecture of Intelligent Manufacturing is expected to provide a clear technical route for future national planning and the development of enterprises as well as a clear plan for matching the standard of intelligent manufacturing in China with other international standards.

References

[1] The Research Group for Research on Intelligent Manufacturinig Development Strategy by New-Generation Artificial Intelligence. Research on intelligent manufacturinig development strategy in China [R]. Beijing: Chinese Academy of Engineering, 2017. Chinese.

[2] Wang S. Considerations on building the reference frame of intelligent manufacturing system [J]. Wisdom China, 2016 (9): 43–45. Chinese.

[3] Wei S. Research on intelligent manufacturing system architecture [J]. Standardization Research, 2016 (4): 50–54. Chinese.

[4] Pan Y H. Heading toward artificial intelligence 2.0 [J].Engineering, 2016, 2(4): 409–413.

[5] Wang C X, Wang C C, Wang S. Comparative study of intelligent manufacturing reference model [J]. Instrument Standardization & Metrology, 2017 (4): 1–7, 42. Chinese.

[6] General Electric Company. Industrial Internet [M]. Beijing: China Machine Press, 2015. Chinese.

[7] Kagermann H, Wahlster W, Helbig J, et al. Recommendations for implementing the strategic initiative Industrie 4.0: Securing the future of German manufacturing industry [R]. The Industrie 4.0 Working Group, Forschungsunion, 2013.

[8] Industrial Value Chain Initiative. Industrial value chain reference architecture (IVRA) [R]. Tokyo: Industrial Value Chain Initiative, 2016.

[9] Ministry of Industry and Information Technology of the PRC, Standardization Administration of the PRC. National intelligent manufacturing standard system guide(2015) [R]. Beijing: Ministry of Industry and Information Technologyof the PRC, Standardization Administration of the PRC, 2015. Chinese.

[10] Zhou J, Li P G, Zhou Y H, et al. Toward new-generationintelligent manufacturing [J]. Engineering, 2018, 4(1): 11–20.