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Understanding of New Generation of Intelligent Manufacturing Based on RAMI 4.0

Zhao Min

Innovation (BJ) NewTech Dev Co., Ltd., Beijing 100083, China

Abstract: To gain a deeper understanding of the significance of the Chinese Academy of Engineering's "China Intelligent Manufacturing Development Strategy Research Report Based on the New Generation of Artificial Intelligence," the author employs the method of deconstruction and reconstruction to analyze the Reference Architecture Model of Industrial 4.0 (RAMI 4.0) of Germany and compares it with the General Architecture of Intelligent Manufacturing (GAIM) proposed by the Chinese Academy of Engineering. The similarities and differences are identified. It is believed that the GAIM in China is superior in terms of intelligence. This is the Chinese contribution to the development of intelligent manufacturing. Moreover, the analysis elucidates both architectures.

Keywords: RAMI 4.0; cyber-physics system (CPS); basic paradigm; new-generation artificial intelligence; architecture; technical dimension; organizational dimension; value dimension

1 Introduction

Since early May 2017, the author has been participating in project discussion and draft revision for the China Intelligent Manufacturing Development Strategy Research Report Based on the New-Generation Artificial Intelligence of the Chinese Academy of Engineering (CAE), which is hereinafter referred to as the CAE Report.

On December 7, 2017, academician Zhou Ji—the former president of CAE—delivered a speech titled *Reflection on China Intelligent Manufacturing Development Strategy* at the World Intelligent Manufacturing Conference in Nanjing, and he later gave the same speech at CAE in January 2018. In the speech, Zhou systematically elaborated the development strategy of intelligent manufacturing in China, arousing great concern and response in the society. The most important theoretical innovation presented in the speech was the classification of the development process of intelligent manufacturing into three stages with three basic paradigms [1]. Such classification is new to the current intelligent manufacturing industry across the globe, and in particular, the definition of the third paradigm as "new-generation intelligent manufacturing" is beyond the theoretical and connotative scope of the current 11 reference architecture models of intelligent manufacturing across the globe [2], thereby providing a unique academic contribution.

To better appreciate the significance of the report, the author analyzes the relatively integrated Reference Architecture Model Industrie 4.0 (RAMI 4.0) [3] and compares its content to that of the CAE Report, thereby providing a deeper insight into the General Architecture of Intelligent Manufacturing (hereinafter referred to as GAIM) and three basic paradigms of China proposed in the report, as well as enabling a deeper understanding of RAMI 4.0.

2 RAMI 4.0 overview

In April 2013, Germany—one of the countries with a long-established leading position in the industry—officially released

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Corresponding author: Zhao Min, Innovation (BJ) NewTech Dev Co., Ltd.., General Manager / Professor-level senior engineer. Major research field is innovative methods / intelligent manufacturing. E-mail:mike_zhaomin@139.com

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the Industrie 4.0 concept at the Hannover Messe and established the Industrie 4.0 platform. The platform secretariat consists of the industry association BITKOM (German Association for Information Technology, Telecommunications and New Media), VDMA (German Mechanical Engineering Industry Association), and ZVEI (German Electrical and Electronic Manufacturers' Association). The Industrie 4.0 platform released the research report *Reference Architecture Model for Industrie 4.0 (RAMI 4.0)* [4] in July 2015. ZVEI released the research report *The Reference Architectural Model RAMI 4.0 and the Industrie 4.0 Component* on October 4, 2015, which was considered by ZVEI to be an important milestone during its collaboration with partners in the standardization of Industrie 4.0, claimed to be the first version of the Industrie 4.0 component to precisely describe Industrie 4.0-compliant production equipment, and believed to "serve companies as a basis for developing future products and business models" [3].

The original report of RAMI 4.0 is difficult to read. Some terms are unsuitable for literal translation and should be paraphrased to make the main points understandable to readers. After continuously studying RAMI 4.0 for more than one year, the author comprehends the themes and basic content of RAMI 4.0, appreciates its accuracy, practicability, and applicability, and believes that RAMI 4.0 has great flexibility and development potential and can be used to understand, extend, and integrate other intelligent manufacturing models such as the Industrial Internet Reference Architecture (IIRA) or the GAIM in the "Development Strategy of New-Generation Intelligent Manufacturing" proposed by CAE [5].

RAMI 4.0 is a three-dimensional (3D) architecture based on a highly modeled concept: constructing and connecting the basic unit in Industrie 4.0—the Industrie 4.0 component—through the three dimensions of Layers, Stream, and Levels, corresponding to the vertical axis, left horizontal axis, and right horizontal axis, respectively, in Fig. 1. Using this architecture, it is possible to perform systematic classification and subclassification of Industrie 4.0 technology. In theory, it is possible for an enterprise at any level to find its own business location in this 3D architecture, where the location refers to one or more distinguishable management blocks composed of the Industrie 4.0 component.

The Reference Architecture Model for Industrie 4.0 is shown in Fig. 1.

Regarding terminology translation, the Chinese translation " 流 " for the word "Stream" (left horizontal axis) has been widely accepted. The term "Hierarchy Levels" (right horizontal axis) is literally translated in most cases as the Chinese phrase " 层次结构 " or " 层次 ," which is difficult to distinguish from the Chinese phrase " 层 " of the vertical axis—a Chinese translation of the term "Layers" in this study. However, as shown by the items described on the right horizontal axis of Fig. 1, the word "Levels" in the term "Hierarchy Levels" would be better translated as " 级 " to convey the Chinese meaning for the rank of system integration and control, which is in accordance with IEC 62264—the international standard for enterprise and control system integration—while the term "Layers" is suitable for expressing the composition of enterprise management.

3 Decomposition and recombination of RAMI 4.0

Each of the six layers of RAMI 4.0—the Asset Layer, Integration Layer, Communication Layer, Information Layer, Function Layer, and Business Layer, from the bottom to the top—can be jointly observed or separately interpreted. Layer-by-layer decomposition and recombination reveals the subtlety in the structure of RAMI 4.0, which raises the following concerns and questions. Given that the contents of an architecture standard are derived from practice and gradually established via refinement and that RAMI 4.0 is likely to have been constantly subject to the process of refinement, abstraction, and optimization, can RAMI retain the industrial "gene" that have been existent for

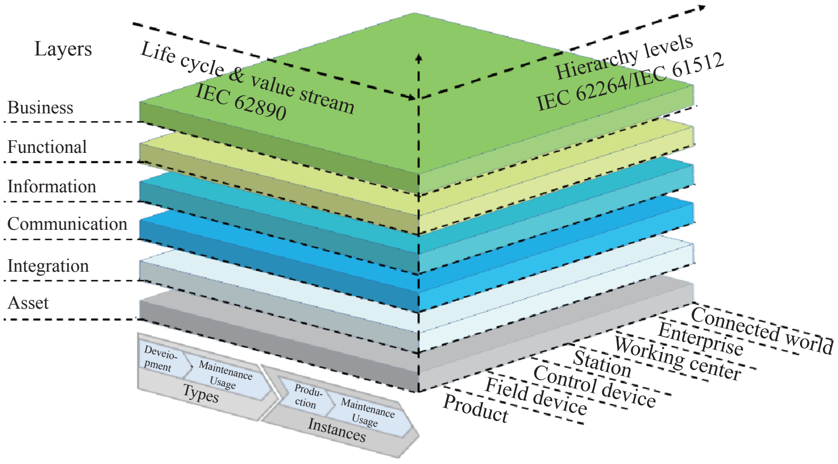


Fig. 1. Reference architecture model for Industrie 4.0.

one or two hundred years so that it can describe the state of corporate management in the early days of the industrial revolution, and can RAMI describe the modern-day third industrial revolution and the upcoming fourth industrial revolution?

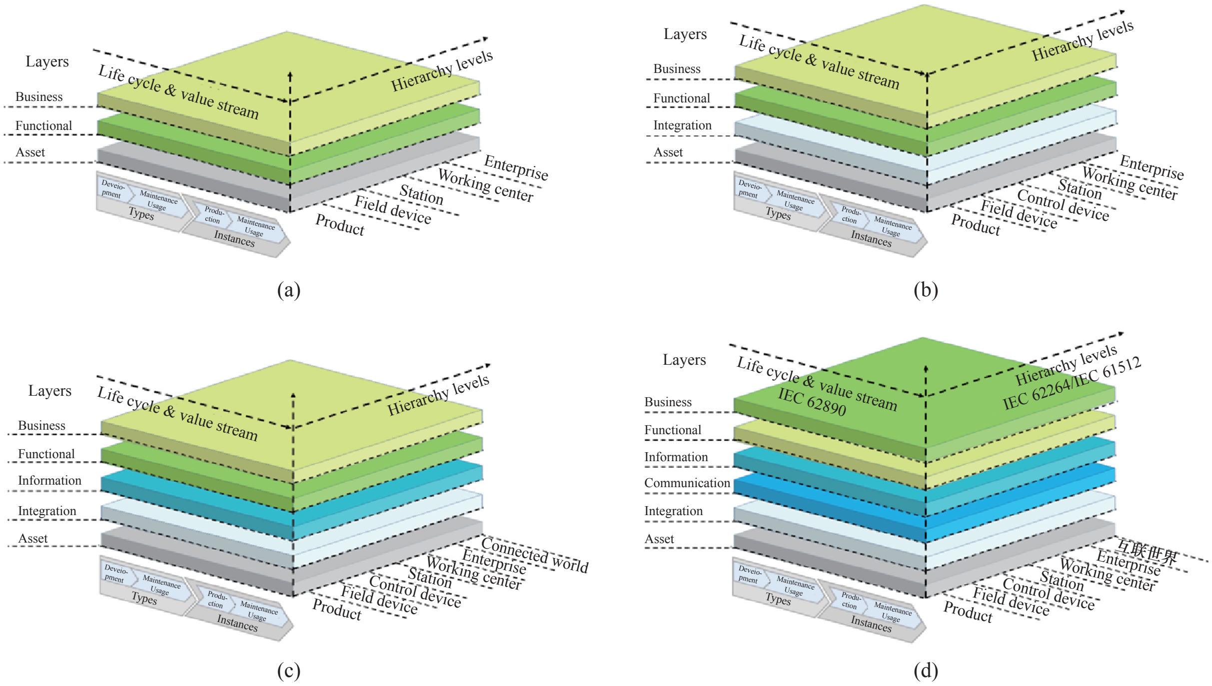
In this study, RAMI 4.0 is decomposed according to the definition of “Layers,” followed by layer-by-layer recombination from the bottom to the top, so that several models are obtained corresponding to different industrial stages, as shown in Fig. 2, and some contents are revealed that are not explicitly expressed but implicitly contained in RAMI 4.0. Although the process of decomposition and recombination does not necessarily fully reflect the original intention of the German design of RAMI 4.0 or accurately match the historical development process of the industrial revolution, the architectural model is an abstract and condensed form of industrial development patterns and extracts the common subject matter while ignoring trivial matters; thus, in this study, the process of decomposition and recombination is considered to be effective for deepening the understanding of RAMI 4.0.

In Fig. 2, the Asset Layer is the basis of business operations. Although the form of the asset varies according to the historical era, its basic nature remains unchanged, which explains why the Asset Layer is involved in the four models, as shown in Figs. 2(a)–2(d). The Function Layer has long existed, even in the past when there was not a clear definition of function—for example, a clear-cut division of labor gradually emerged in the steam engine era, and the division was usually in accordance with the function of the structural components of products. In contrast, the Business Layer has always been existent since the appearance of the basic enterprise unit “factory”—both the intra-factory activity planning and the extra-factory transaction process fall within the management scope of the Business Layer of the factory.

As shown in Fig. 2(a), Industrie 1.0 has a limited number of enterprise activity layers, which are only comprised of the most basic layers: the Asset Layer, Function Layer (not obvious), and Business Layer. Thus, the management is relatively simple, and the machines generally lack control devices. As observed from the aspects of two stages (Prototype, Physical Object) at the Stream dimension, the product research and development (R&D) process is based on engineering blueprints for product design and physical objects for product prototyping. All R&D and production processes are conducted in a serial manner; that is, only after one section is completed can the next be started.

As shown in Fig. 2(b), the Integration Layer is introduced into Industrie 2.0. With the use of electric energy, machines are subject to control by an increasing number of electromechanical control devices, which allow enterprises to have a greater control capability for production activities. Thus, equipment that previously had to be manually adjusted can now be automatically adjusted using electromechanical control devices, leading to a larger number of enterprise activity layers and greater diversity of activity contents. Product R&D is based on blueprints and clay/wood models for product design and physical objects for product prototyping. R&D and production are conducted in serial processes.

As shown in Fig. 2(c), the Information Layer is introduced



(a) (b) (c) (d)

Fig. 2. Four models after the decomposition and recombination of RAMI 4.0.

into Industrie 3.0, which greatly diversifies the management and control methods that an enterprise can use. Digital devices such as programmable logic controllers and embedded systems are introduced into products and equipment, and enterprises are beginning to include digital R&D methods such as CAD/CAE/CAM in the design tools. Equipped with a digitizing and networking capability, the enterprises exhibit a dramatically increased number of activity layers with more activity levels; the product R&D process starts to adopt two-dimensional blueprints and 3D models for product design and digital objects for product prototyping. Parallel engineering is introduced into the R&D process, and numerical control equipment is gradually adopted and eventually prevails in the production process.

Fig. 2(d) depicts a future digital factory (DF) or a smart factory (SF) in the framework of Industrie 4.0. Managing enterprises by using a DF or SF as the smallest enterprise unit is the basic idea of Industrie 4.0. In the Hierarchy Levels dimension, this idea manifests as "vertical integration"; in the Stream dimension, it manifests as "end-to-end integration" based on the whole life cycle of products (or devices, equipment, workstations, etc.); in the Layers dimension, it manifests as a cyber-physical system (CPS). The most difficult step is "horizontal integration," which requires seeking a solution from the "connected world" of the model [4], as "horizontal integration" represents integration between companies in different industries, so that all participants must negotiate on issues such as synergy (who will lead), circles (who will participate), standards (which are to be used), and benefit distribution (who will benefit) and make compromises with one another on the basis of consensus for working synergistically, creating business value jointly, and sharing benefits rationally. There are two main ways for enterprises to integrate with one another in the "connected world" manner, as shown in Fig. 3.

Fig. 3(a) shows a typical "central enterprise" or large group enterprise model. The connecting lines in the figure show the flow of business instructions and information between enterprises and the "headquarters" at the center. Cooperation (i.e., mutual connection) between members of the central enterprise is classified as "horizontal integration." For example, the development of an aircraft carrier must involve cooperation between members of military-related central enterprises. Fig. 3(b) shows the more frequently encountered cooperation between mutually independent enterprises in the same industry or in different industries, with only collaboration and information flow but no instructions present between the enterprises. Enterprises in different industries can also form "horizontal integration" by jointly developing a large, complex product project. In the future, under various forms of Internet support, inter-enterprise cooperation is likely to be achieved through the mixed mode of "Fig. 3(a) + Fig. 3(b)," with a bias toward the mode of Fig. 3(b).

The "Connected World" formed by the internal and external networking of enterprises has given rise to the Industrial Internet (or Industrial Internet of Things). In this sense, although the reference architectures used in the industrial development paradigms of Industrie 4.0 and Industrial Internet differ and the starting point for model construction may not be the same, the enterprises are inevitably led to the same outcome, regardless of which architecture is adopted.

4 Three basic paradigms and CPS of intelligent manufacturing

Academician Zhou Ji repeatedly mentioned that Industrie 3.5 or a slightly higher level can be fully achieved using the existing standards and technical element support, but the German Industrie 4.0 cannot be achieved unless new-generation artificial intelligence (AI) becomes available. In this context, the concept of "True Industrie 4.0" is formally proposed, which is also mentioned in the CAE Report: "If smart manufacturing is deemed the beginning of the new round of industrial revolution, then the breakthrough and widespread application of a new-generation intelligent manufacturing will promote the occurrence of the climax of this round of industrial revolution, reshape the technical system, production mode, and industrial pattern of manufacturing industries, and play a leading role in True Industrie 4.0, thereby leading to full realization of the fourth industrial revolution." [1]

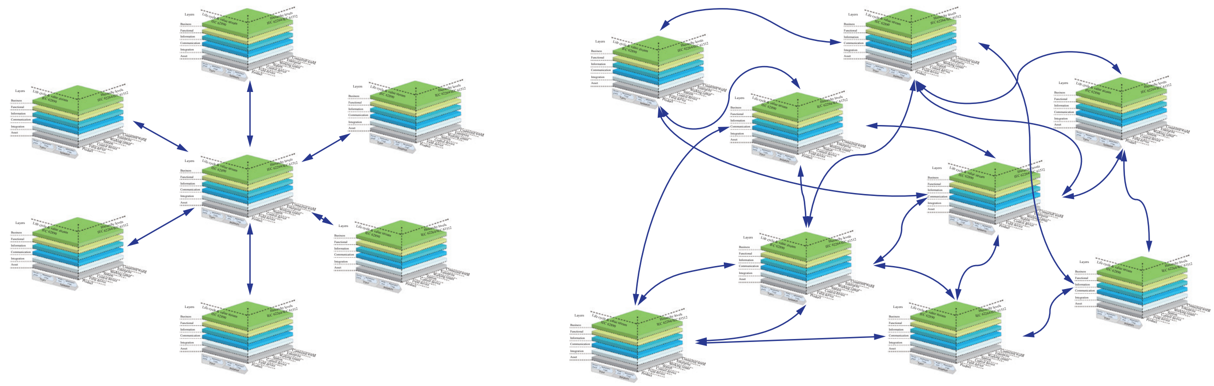


Fig. 3. Two basic modes of enterprise connection.

In the CAE Report, three basic paradigms of intelligent manufacturing are defined, as shown in Fig. 4.

The first paradigm "digital manufacturing" has been extensively documented in the literature and is not elaborated in this article.

According to the CAE Report, "smart manufacturing" belongs to the second development stage and the second paradigm of intelligent manufacturing. In this paradigm, the digital networking technology has undergone great development, with a deep integration between a variety of networks (not only the Internet) and the manufacturing industry, and CPS has become the mainstream enabling technology for intelligent manufacturing.

According to the "three-body intelligence model" presented in the book *Three-Body Intelligence Revolution*, the interaction and fusion between the digital virtual body (alternatively expressed as the "cyber system" in the CAE Report) and the physical entity (alternatively expressed as the "physical system") leads to the formation of a CPS [6]. The emergence of the CPS is a milestone. From the late 1980s to the beginning of the 21st century, Japan's fifth-generation computer project and the Intelligent Manufacturing System project—both of which were launched to promote AI development—failed, making AI research hit rock bottom for the second time. People began to seek a new technology for building intelligent systems. In 2006, Helen Gill of the US National Science Foundation (NSF) proposed the concept of the CPS, which quickly triggered positive responses in industrial countries such as Germany. As a type of intelligent agent for digital networking, the CPS is the "greatest common divisor" between Industrie 4.0, intelligent manufacturing, and Industrial Internet and is also their key enabling technology. It can even be said that future world will take the form of a CPS.

The proverb of "state perception, real-time analysis, autonomous decision-making, precise execution, and learning promotion" proposed in the book *Three-Body Intelligence Revolution* provides a good description of the basic logic of the CPS intelligent agent [6] and has been included as a major viewpoint in the *White Paper on Cyber-Physical Systems (2017)* issued by China Electronics Technology Standardization Institute, Ministry of Industry and Information Technology [7].

Research groups from different countries have different understandings of the CPS. From the viewpoints of common sense and literal translation, CPS refers to a typical two-body interaction between C (digital virtual body) and P (physical entity). However, with the continual explicitation of implicit knowledge in the human brain, explicit knowledge is continuously optimized, screened, and accumulated, and human intelligence with knowledge as the carrier is continuously digitized, coded, and transformed into artificial systems to form machine intelligence. With the continuous increase of machine intelligence relative to human intelligence, the human brain is gradually withdrawn from the system loop of "perception–analysis–decision–execution" and eventually disappears in the system loop, but human intelligence still resides in the artificial system in the form of digital software, where human intelligence functions as a "knowledge engine" in the system loop to drive the implementation of intelligent systems, such as intelligent manufacturing.

With regard to the effects of the conscious-human body (the CAE Report adopts the concept "human," which is divided into "human body," "human brain," and "human consciousness" in this study) on the CPS, Chinese scholars have a broader understanding than scholars from the US and Germany. In this study, it is considered that even if the human brain is withdrawn from the system loop, the human brain will engage in knowledge production in a professional manner based on a more rational

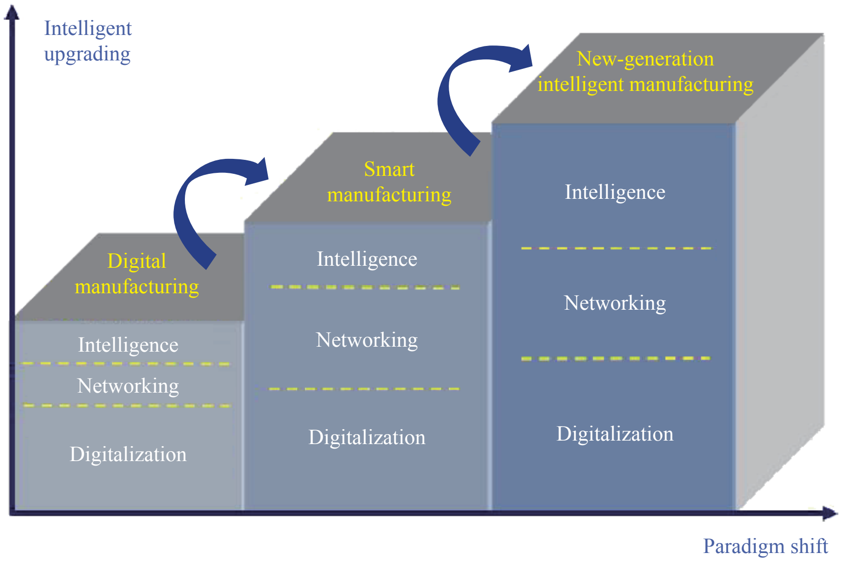


Fig. 4. Evolution of the basic paradigms of intelligent manufacturing.

division of labor. In the future, human intelligence will continuously enter the digital virtual body to promote the increase of machine intelligence. The CPS, which appears to be a result of two-body fusion, is essentially a result of three-body fusion. It is considered that the human influence on the CPS has always been present and has always played a dominant role in the formation and development of the CPS. Human intelligence is the dominant and decisive factor in intelligent manufacturing (this view is basically consistent with the connotation of Human-Cyber-Physical Systems (HCPS) in the CAE Report).

Software is an important carrier of the digital virtual body. It can be used to define many new rules under the constraint of hardware feasibility, while human intelligence resides in software in the form of digital knowledge to define reasoning and judgment rules for software. Replacing the human brain with human intelligence and allowing the latter to be present in the loop in the form of software is the main function that the CPS can provide as an intelligent agent of digital networking. The universal application of the CPS can be used as a technical element to judge whether the second paradigm, i.e., smart manufacturing, is realized.

The German Industrie 4.0 is proposed to be achievable through the CPS. However, to realize the True Industrie 4.0 defined by CAE, it is mandatory to conduct further technical updates and a paradigm shift on the basis of CPS-based smart manufacturing, i.e., shifting to new-generation intelligent manufacturing based on new-generation HCPS technology.

5 Similarities and differences between RAMI 4.0 and China's GAIM

Wang Chunxi et al. [2] found that the reference architectures of intelligent manufacturing are dominated by 3D architectures, and most of Germany's RAMI 4.0, US IIRA and SMS, Japan's IVRA, China's early IMSA, and the Global 3D maps proposed by the International Organization for Standardization are 3D reference architectures. Therefore, the proposed General architecture reference for intelligent manufacturing in the CAE Report is also a 3D architecture, in accordance with the mainstream trend of reference architectures.

According to the CAE Report, "Intelligent manufacturing covers the theories, methods, technologies, and applications involved in the whole life cycle of products, manufacturing, and services." The GAIM can be described using three dimensions: a value dimension centered on production, a technology dimension focused on the integration between informatization and industrialization (hereinafter referred to as IBII), and a people-oriented organization dimension, as shown in Fig. 5 [5].

The three dimensions in the GAIM are defined as follows.

Value dimension—a dimension centered on production for value realization. The value realization of intelligent manufacturing is mainly reflected by three aspects—product, production, and service—as well as in the system integration.

Technology dimension—a technical evolution dimension focused on the IBII. With regard to technical evolution, intelligent manufacturing manifests as three basic paradigms: digital manufacturing, smart manufacturing, and new-generation intelligent manufacturing.

Organization dimension—a human-oriented organization system dimension. The organization systems that implement intelligent manufacturing consist of three levels of systems: intelligent units, intelligent systems, and system of systems (SoS) [5].

Given that the GAIM is 3D, although there are differences in the design details of dimensions between the GAIM and RAMI 4.0, most of the contents in one architecture can be directly mapped or approximately mapped to counterparts in the other

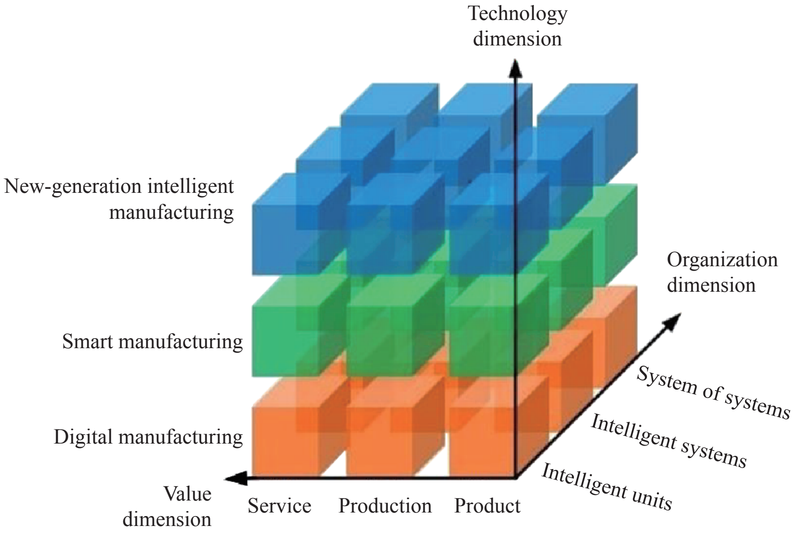


Fig. 5. Three dimensions in the GAIM.

architecture, as shown in Fig. 6.

On the left horizontal axis, the two architectures are consistent with each other regarding the contents of the life cycle of the value stream, except that the Stream in Fig. 6(a) is slightly implicit and embedded in the whole life cycle consisting of three stages (Product, Production, Service), where two sub-stages (Type and Instances) are also hidden, whereas the Stream in Fig. 6(b) only contains the two stages of Type and Instances.

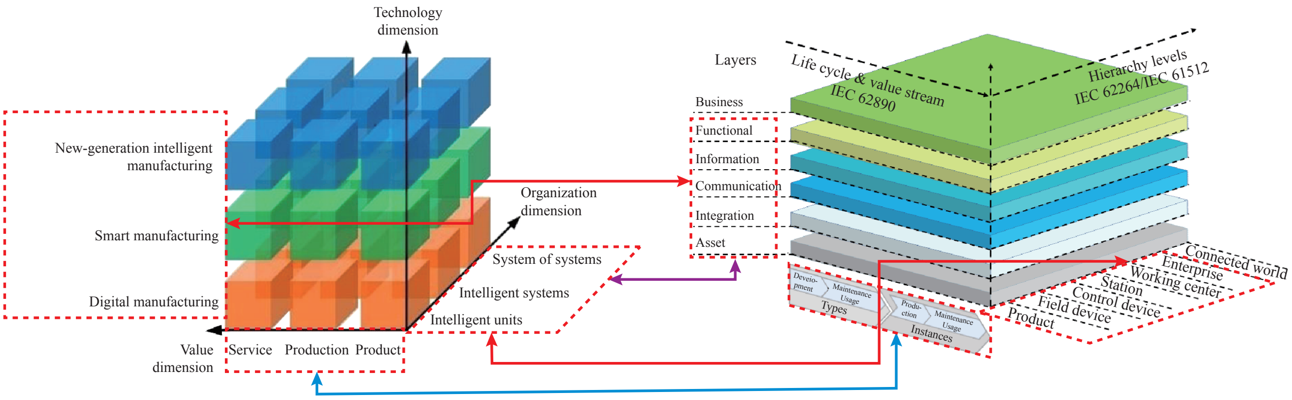
On the right horizontal axis, Fig. 6(a) shows the three system levels of Unit, System, and SoS in the organization dimension and highlights the participation of human-oriented human intelligence; that is, the three system levels are all composed of HCPS, making the right horizontal axis conceptually abstract. Fig. 6(b) presents a more detailed classification of the system levels and even proposes the level of the extended Connected World, but the levels only refer to equipment, and it is not certain whether they involve human participation. An alternative interpretation may be that RAMI 4.0 implicitly involves human participation in its Asset Layer, where humans are treated as a passive management element rather than an active one.

On the vertical axis, Figs. 6(a) and 6(b) are significantly different. Fig. 6(a) shows the layers of IBII and the layers of system intelligence, indicating large, abstract concepts. Additionally, Fig. 6(a) highlights the introduction of new-generation AI. In Fig. 6(b), the layers refer to the technical layer and enterprise management layer for system/component implementation, as well as the resultant CPS. Therefore, there is no one-to-one mapping between the two architectures on this axis, except that the two architectures have some elements in common—for example, the digitalization and networking in Fig. 6(a) can be well mapped to the integration layer, communication layer, and information layer in Fig. 6(b). However, the Asset Layer clearly marked in Fig. 6(b) is difficult to locate in Fig. 6(a), which may be attributed to the presence of this layer in both the Organization Dimension and the Technology Dimension.

In summary, Fig. 6(a) is more macroscopic and abstract than Fig. 6(b), and it has a wide application range including but not limited to the SF, making it more adaptable to China's complex situation involving IBII and multiple paradigms. Fig. 6(b) is more microscopic and specific and is oriented to the construction of the SF, with a greater focus on intra-enterprise smart and the extra-enterprise "Connected World."

Despite the many identical or similar elements between the two architectures, new-generation AI, as an element, is explicitly missing in RAMI 4.0, which also does not highlight human elements. However, these two types of elements are explicitly included as core support elements in the GAIM.

Given the aforementioned contrast, a bold hypothesis is presented in this article: to convert RAMI 4.0 into an architecture of True Industrie 4.0, it should be modified slightly, at least in the Layers dimension, where contents relevant to new-generation AI should be explicitly introduced. To visualize the corresponding relationship between the improved architecture and the original architecture, a hypothetical architecture referred to as RAMI 4.0-AI is proposed herein, where an AI algorithm layer is inserted between the Information Layer and the Function Layer. In RAMI 4.0, the role of the Function Layer is to achieve a formal description of function and form decisions based on the application scenarios at the lower layers. The role of the Information Layer is to provide a formal, digital description of rules and mechanism models and to execute and run the rules and mechanism models related to specific events. The carrier of the Information Layer is software in which all rules and mechanism models (algorithms) are embedded. It is well known that AI usually manifests as an algorithm, and whether a software is an AI software can be determined by evaluating the algorithm and its big-data processing capability. Apart from being a basis on which AI can be established, the algorithm is an active element that undergoes rapid improvement and change. Therefore, adding an "AI layer" between the Information Layer and the Function Layer without evoking a major change to the original structure of RAMI 4.0 is a relatively



(a) (b)

Fig. 6. Mapping of the GAIM and RAMI 4.0.

convenient improvement method that allows the gradual inclusion of new-generation AI algorithms in the existing software for achieving True Industrie 4.0 (new-generation intelligent manufacturing), as shown in Fig. 7.

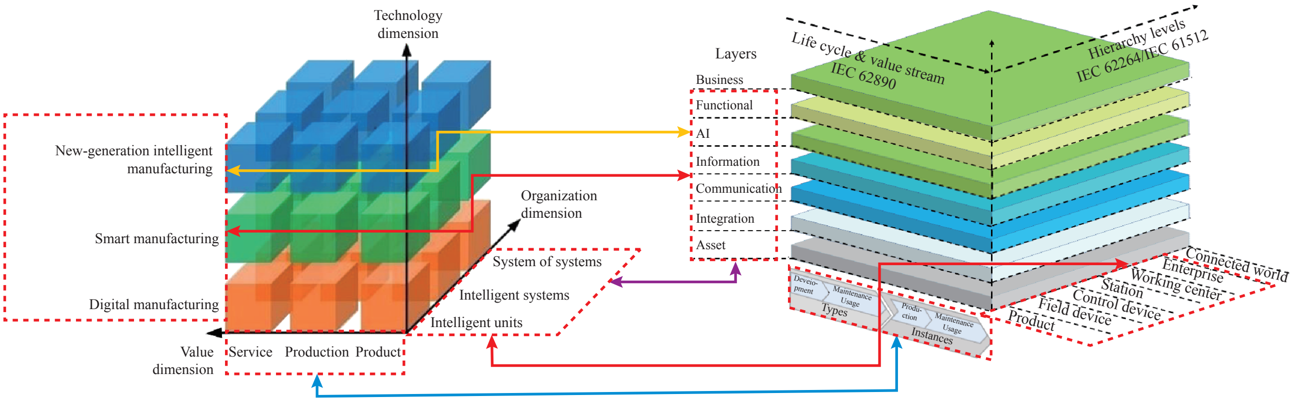
It is evident that the GAIM shown in Fig. 7(a) has a better corresponding relationship with the hypothetical RAMI 4.0-AI depicted in Fig. 7(b). Comparison of the two figures provides deep insight into the similarities and differences between the two architectures.

6 Conclusion

The CAE Report proposes three stages with three basic paradigms in the development of intelligent manufacturing, clarifies the development path and technical rules, and establishes the architecture of True Industrie 4.0, representing China's contribution to the development of intelligent manufacturing.

RAMI 4.0 well embodies CPS-focused smart manufacturing; however, this architecture lacks support from new-generation AI technology and the new-generation HCPS, and hence, it is unable to accommodate more than two paradigms. Regarding the realization possibility of intelligent manufacturing, the GAIM proposed by CAE is superior to that of RAMI 4.0.

To realize the third paradigm of new-generation intelligent manufacturing, it is mandatory to rely on new-generation AI as a core technology and new-generation HCPS as a technical element and to construct the paradigm according to the GAIM proposed in the CAE Report. Alternatively, it may be possible to modify the existing RAMI 4.0 and use the RAMI 4.0-AI architecture to approximate the GAIM.



(a) (b)

Fig. 7. Relationship between improved RAMI 4.0-AI and GAIM.

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