

Received August 5, 2020, accepted August 25, 2020, date of publication September 4, 2020, date of current version September 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3021719

Study on the Reference Architecture and Assessment Framework of Industrial Internet Platform

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This work was supported in part by the National Natural Science Foundation of China under Grant 61771281, in part by the National Social Science Foundation of China under Grant 15ZDB151, in part by the National Key Research and Development Program of China under Grant 2018YFF0213700, and in part by the 2018 Industrial Internet Platform Innovation and Development Project of China.

ABSTRACT With the continuous innovation of new-generation information technology and its accelerated integration with manufacturing industry, industrial internet platforms (IIPs) are rapidly emerging worldwide. Construction and application of IIP has become a new focus in international competition for leading enterprises, and also a new direction of industrial development for many countries worldwide. However, the development of IIP is still in the stage of exploration, and the industry sector still lacks unified understanding of the IIP. Therefore, this study firstly proposes a reference architecture of IIP to clarify its framework and core functions, so as to provide a general reference model for the industry to understand and jointly promote construction of IIP. Secondly, an assessment system is proposed to evaluate the usage of IIP. The assessment framework is composed from three domains namely the foundation, key capability, value and benefit. Finally, the practical value of the reference architecture and the assessment framework of IIP is verified by an industry practice.

INDEX TERMS Industrial Internet platform (IIP), reference architecture, assessment framework, assessment indicator.

NOMENCLATURE

IIP	industrial internet platform.
CPS	cyber-physical system.
IoT	Internet of things.
IIoT	Industrial Internet of things.
IT	information technology.
OT	operation technology.
ERP	enterprise resource planning.
MES	manufacturing execution system.
PHM	prognostic and health management.
SCADA	supervisory control and data acquisition system.
PLC	programmable logic controller.
DCS	distributed control system.
PLM	product lifecycle management.
SOA	service-oriented architecture.
IaaS	infrastructure as a service.
PaaS	platform as a service.

SaaS	software as a service.
IIC	Industrial Internet Consortium.
AII	Alliance of Industrial Internet.

I. INTRODUCTION

In recent years, the internet of things, cloud computing, big data, artificial intelligence and other new-generation information technologies continuously innovating and integrating into manufacturing industry, industrial internet platforms (IIPs) are rapidly emerging worldwide which have brought about new opportunities for the upgrading of the manufacturing industry. General Electric Company (GE) puts forward the concept of IIP for the first time in November 2012, and subsequently established the Industrial Internet Consortium (IIC) in cooperation with AT&T, Cisco, Intel and other institutions, to vigorously promote the application of its industrial internet platform-Predix. With potential of more intelligent and efficient industrial production, the industrial internet platform has attracted widely concern by the global

The associate editor coordinating the review of this manuscript and approving it for publication was Firooz B. Saghezchi¹.

industry sector [1]. Following GE, global industrial giants and leading ICT enterprises have developed their IIP products based on their own advantages [59]–[61], such as Siemens MindSphere, ABB Ability, PTC ThingWorx, Amazon AWS, Haier COSMOplat, Alibaba ET Industrial Brain, etc. Accenture forecasts that global investment in the IIP will exceed \$15 trillion by 2030 [2].

IIP can carry industrial data, industrial knowledge, industrial application services and other resources, provide advanced analysis and human-machine interaction capabilities, and support ubiquitous connection, flexible supply and efficient allocation of manufacturing resources [3]. The industry generally believes that IIP play an important role in helping enterprises to improve efficiency and flexibility, and reduce costs. For example, GE puts forward the concept of “the power of 1%” and believes that even if the IIP increases efficiency by 1%, the benefits will be huge [4]. At present, the wide application of IIP has strongly promoted the process of enterprises’ digital transformation and accelerated industrial innovation and development. However, in general, the global development of IIP is still in the stage of exploration and the industry still lacks unified understanding of the IIP. It is of great significance to study general reference architecture and to form a scientific assessment system in order to guide development of IIPs.

In the field of IIP reference architecture, some institutions and researchers have carried out relevant researches to discuss the function and value of IIP [5]. For example, Industrial Internet Consortium (IIC) [6] and Alliance of Industrial Internet(AII) [7] put forward the reference framework of industrial internet, which are suitable for their own national conditions. Aiming to manage the interaction between the physical and cyber components, Wang *et al.* [8] proposed a collaborative architecture for IIP called industrial operation system (Ind-OS), to provide a better cooperative enterprise information system (EIS) environment for manufacturing systems. Yang *et al.* [9] analyzed the industrial internet application based on 5G edge computing, and presented the technical architecture of 5G industrial Internet edge computing.

Whereas in the field of IIP assessment, IIC [10] and AII [11] and some researchers have conducted relevant researches to evaluate the usage of IIP. For example, a vulnerability assessment method based on attack graph and maximum flow is proposed to solve the problem of quantification of attack paths and complex path finding in the industrial internet of things [12]. Radanlieva *et al.* [13] focused on the economic impact assessment of IoT and its associated cyber risks. In [14], a continuous risk monitoring was considered in the context of cybersecurity management for the IIoT. Adamsky *et al.* [15] highlighted the main security challenges for risk assessment, and proposed a security framework to properly manage vulnerabilities, and to timely react to the threats. Nevertheless, these studies mainly focus on certain parts of platform development, such as discussions on performance and security, but there is still a lack of in-depth and comprehensive research on IIP assessment framework.

In order to address these problems above, this study proposes a novel reference architecture and an assessment system of IIP. Compared to the previous studies, our contributions are as follows:

- 1) An reference architecture of IIP is built, which covers the platform’s core functions like distributed IT resource scheduling and management, industrial resource ubiquitous connection and allocation, industrial big data management and mining, industrial microservice supply and management, and lifecycle environment and tools services for industrial APP as well.
- 2) The assessment framework of IIP is constructed from three domains namely foundation, key capability, value and benefit. In addition, the assessment indicators and assessment method are provided as well.
- 3) An assessment system is established to evaluate the usage of the IIP collect, and its practical value is verified by an industry practice.

The rest of this study is organized as follows. Section II briefly reviews related works. Section III describes IIP reference architecture and Section IV provides IIP assessment framework and indicators. Section V gives an industry practice to verify the application value of the reference architecture and assessment system of IIP. Section VI wraps up with a brief discussion and summary.

II. STATE OF THE ART

A. HISTORY OF IIP

Nowadays, traditional manufacturing driven by modern technologies such as cyber-physical systems (CPS), internet of things (IoT), industrial internet, intelligent manufacturing, digital twin and cloud manufacturing, is transformed into a digital ecosystem [16]. In order to distinguish the differences between these technologies and concepts, it is necessary to return to the industry itself to explore the history of these technological concepts. As IIP is the product of the integration of information technology(IT) and operation technology(OT), it not only emphasizes the collection, analysis and processing of industrial data, but also strengthens the integration of enterprise information systems such as enterprise resource planning (ERP), manufacturing execution system (MES) and prognostic and health management (PHM) to improve enterprise management performance [17]. Therefore, this study analyzes the development history of IIP from the perspective of enterprise information management and industrial control network.

1) MANUAL MANAGEMENT OF ENTERPRISE INFORMATION SYSTEM

From the early 20th century to the 1980s, various theories of enterprise information management emerged, such as Taylor’s scientific management method based on human factor engineering, Goldratt’s theory of constraints (TOC), Toyota’s lean production based on the purpose of reducing inventory, Motorola’s six sigma management based on

improving enterprise quality process. Although some monolithic applications are used in enterprise, the integration method among different systems adopts point-to-point communication to deliver information, which must be managed and maintained by human. These monolithic applications are not widely used, and the cost of development is too high.

2) SEPARATE DEPLOYMENT OF ENTERPRISE INFORMATION SYSTEM

In the 1990s, Gartner Group put forward the concept of ERP, advanced manufacturing research (AMR) proposed concept of MES, combined with the supervisory control and data acquisition system (SCADA), and the American national standards institute (ANSI) developed a classic five-tier architecture for enterprise management. As shown in Figure 1, it is established based on ISA95 which contains five levels according to the architecture defined in the ‘‘Purdue Enterprise Reference Architecture’’ (PERA). Level 0 is the shop floor, which is associated to the physical process of manufacturing, involves sensors, actuators, and other devices. Level 1 is the work unit, which involves various micro-processor, for example, Programmable Logic Controller (PLC), Microcontroller Unit (MCU), etc. Level 2 is the workshop, which involves some simple control system, for example, SCADA, Fieldbus Control System(FCS), distributed control system (DCS), etc. Level 3 is Plant, which involves the management of the operation in the production of the desired products, manufacturing execution/operation management system (MES/ MOM) and related middleware are employed at this level. Finally, level 4 represents the business activities of the enterprise, which includes ERP, product lifecycle management (PLM) and some other systems.

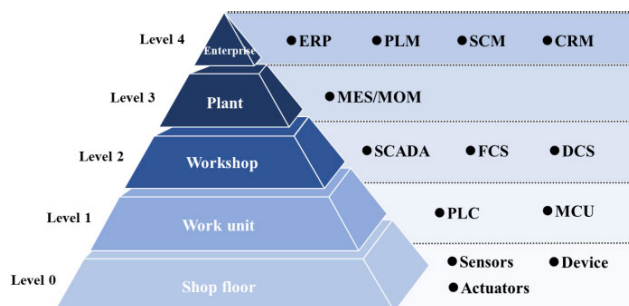


FIGURE 1. Enterprise information system architecture.

When the above five-tier systems are integrated, data parsing is usually done by developing middleware at each level separately. In particular, each level interacts only with its adjacent levels. This manufacturing architecture is established on standalone client/server data base applications that attempted to represent business process modeling through point-to-point interfaces and custom data transformation between applications. During this period, most enterprise information systems were largely isolated from conventional digital networks, resulting in a large number of data silos.

3) THE SERVICE-ORIENTED ARCHITECTURE FOR ENTERPRISE INFORMATION SYSTEM

At the beginning of the 21st century, the enterprise information system are gradually transitioned to a service-oriented architecture (SOA). Various management systems began to adopt the enterprise service bus (ESB) for communication and integration, the unified and open interface standard and communication mechanism have been developed, and the closed loop of data transmission among ERP, MES and SCADA has been preliminarily realized. However, due to the centralized management mode of the ESB itself, the ESB communication mode is not widely used in the integration of enterprise information systems.

4) SOFTWARE AS A SERVICE FOR ENTERPRISE INFORMATION SYSTEM

In 2006, the concept of cloud computing was proposed, which marked the entry of enterprise information systems into the era of cloud-based software. Cloud computing service are generally divided into three categories: infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). Major Internet companies have launched cloud computing service, such as Amazon AWS, Windows Azure, Google App Engine and Alibaba Cloud.

5) INDUSTRIAL INTERNET PLATFORM

In recent years, with the development of IoT, the implementation costs of big data, artificial intelligence and other new generation of information technology continue to reduce. It enables the hardware and software needed for IIP to be deployed in a cost-effective and reliable manner, thus the development of enterprise information system has entered a new historical period.

B. NEW GENERATION OF INFORMATION TECHNOLOGY

In 1999, the Massachusetts Institute of Technology (MIT) put forward the concept of Internet of things (IoT) [18] based on Radio Frequency Identification (RFID) technology. In their definition, industrial internet of things (IIoT) is the application of IoT in industrial field. It is to integrate all kinds of sensors with sensing and monitoring ability into each link of industrial production process, so as to realize the interconnection between industrial equipment, products, process and enterprise information management system.

In 2006, Helen Gill in the America’s national science foundation(NSF) came up with the idea of Cyber Physical System (CPS) [19], which considered as the core of Industry 4.0. CPS emphasizes the real-time, dynamic feedback and cyclic process between the physical world and the cyber system. It deeply integrates many types of technologies to make all kinds of information capabilities highly collaborative and autonomous, and realizes the production system to independently, intelligently, dynamically and systematically monitor and change the characteristics of the physical world.

In 2011, the Air Force Research Laboratory (AFRL) proposed the use of Digital Twin to solve the maintenance problem of fighter jets [20]. Digital Twin makes full use of physical model, sensor data, operation history and other data, integrates multi-disciplinary, multi-scale and multi-domain simulation process, so as to reflect the whole life cycle process of corresponding physical equipment.

In 2012, GE puts forward the concept of the Industry Internet Platform (IIP) [4] in the world for the first time, its essence is to connect equipment, production lines, factories, suppliers, products and customers closely through the industrial internet. It helps to form cross-equipment, cross-system, cross-factory and cross-region connectivity, promotes the leapfrog development between manufacturing and service industries, and enables the efficient sharing of various elements and resources of the industrial economy. IIP adopts the micro-service architecture, integrates the business system through the “middle platform”, and accumulates all the data generated by the industry by using the data lake method. The information gap between different enterprise information systems is broken through service mesh technology. The detailed system architecture will be introduced in Section III.C.

Through the elaboration of the above four technical concepts, we can observe that the granularity of technical level is roughly digital twin, CPS, Industrial Internet of things, Industrial Internet. The digital twin is the basis of CPS, which emphasizes the mapping of the whole life cycle of physical entity to the digital twin of virtual world, to realize real-time simulation optimization decision. CPS emphasizes the real-time collection, communication and calculation of information between physical space and cyberspace, so as to realize the real-time perception, dynamic control and optimization decision of the engineering system. IIoT is the extension of the CPS concept. It employs the IoT technology to connect the equipment inside the factory and the industrial products to the enterprise management system. IIoT technology mines the accumulated industrial historical data through the big data technology to highlight the value of the data and realize the improvement of quality, cost and efficiency of the enterprise. Industrial Internet extends the concept of IIoT to the scope of social and economic fields. It not only focuses on the connection of industrial field equipment and external products, but also enhances the value of industrial chain through various innovative service modes.

C. COMPARATIVE ANALYSIS OF RELEVANT ARCHITECTURES

The industrial internet originated from IIoT and expanded its boundaries, which initially focused on manufacturing systems. It could be expanded to the scope of socio-economic fields, realizing the mutual connection and sense of more fields through the analysis of the new generation of information technology by intelligent devices. The starting point of the industrial internet and smart manufacturing are the same, both are committed to using digital technology to improve the key performance of manufacturing system. Therefore, it is

necessary to compare and analyze the reference architecture of industrial internet and intelligent manufacturing proposed in various countries nowadays.

1) REFERENCE ARCHITECTURE OF INDUSTRIAL INTERNET

Industrial Internet Consortium (IIC) published industrial internet reference architecture (IIRA) version 1.9 in 2019. As shown in Figure 2, IIRA is divided into five functional domains, including business domain, operation domain, information domain, application domain and control domain, forming data-analysis-centered integration. IIRA focused on cross-industry versatility and interoperability, provided a set of methods and models to drive system design with business value, and used data analysis to promote end-to-end optimization of industrial network system. Benefited from the IIRA, the United States applied industrial internet to manufacturing, transportation, energy, medical and other industries.

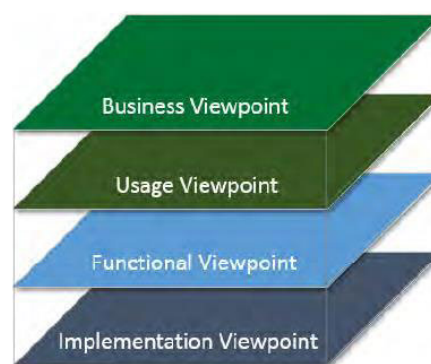


FIGURE 2. Viewpoints of Industrial Internet Reference Architecture [21].

2) REFERENCE ARCHITECTURE OF INDUSTRY 4.0

Based on Germany's strong manufacturing capabilities, the Industry 4.0 Reference Architecture Model (RAMI4.0) [22] is proposed to describe the 3D reference architecture model of Industry 4.0. As shown in Figure 4, it emphasizes the integration of three aspects, including the vertical integration of the internal networked manufacturing system of the enterprise, the horizontal integration between enterprises and the end-to-end engineering digital integration of the entire life cycle.

RAMI 4.0 focuses on the manufacturing process and life cycle, which is very valuable for analyzing the functions of different units in the manufacturing environment and determining the interoperability requirements between them. The related Industry 4.0 components play an important role in facilitating the comprehensive interconnection of various systems in the manufacturing environment.

3) REFERENCE ARCHITECTURE OF INDUSTRIAL VALUE CHAIN

The Industrial Value Chain Initiative (IVI) is an organization initiated by manufacturing enterprises, equipment manufacturers, system integration companies, etc. Its purpose is to

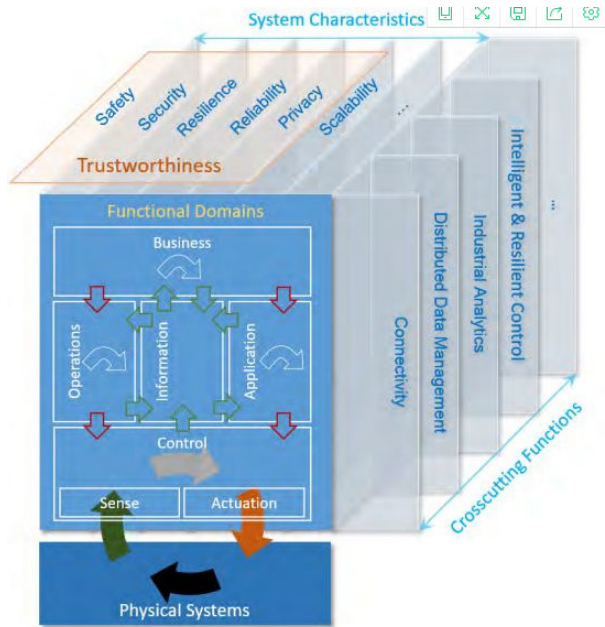


FIGURE 3. Functions of Industrial Internet Reference Architecture [21].

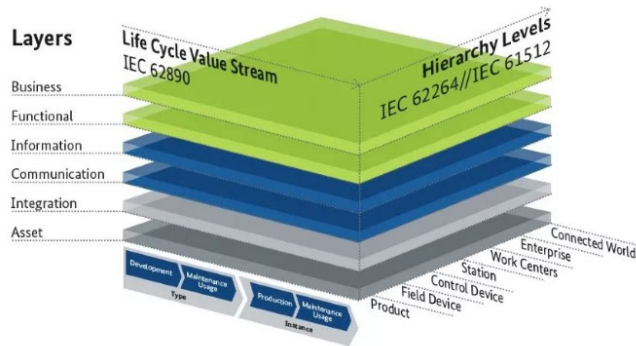


FIGURE 4. Reference Architecture of Industry 4.0 [22].

promote the realization of “smart factory”. In 2016, IVI introduced the basic architecture of the smart factory. The Industrial Value Chain Reference Architecture (IVRA) [23] puts forward the top guiding principles for realizing enterprise interconnection. IVRA is basically similar to RAMI4.0. As shown in Figure 5, it is also a three-dimensional model that describes the activities of the manufacturing site from three aspects: asset, activity and management.

Compared with RAMI4.0 and IIRA, one of the main functions of IVRA is that it has “onsite” functions, including specific employee cooperation. IVRA embeds the unique value orientation of “Made in Japan” and is expected to become another standard for global smart factories.

4) INDUSTRIAL INTERNET ARCHITECTURE 2.0

In 2019, China Alliance of industrial internet (AII) released Industrial Internet Architecture (IIA) version 2.0 [24]. The architecture includes three aspects: the business view, function architecture and implementation framework.

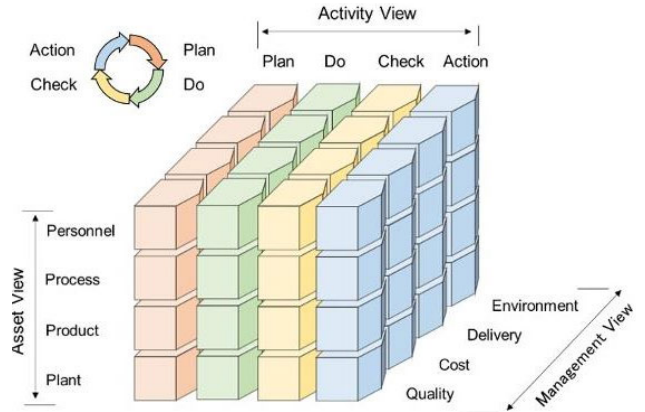


FIGURE 5. 3D model of IVRA[23].

Through the construction of the three major functional systems of network, platform, and security, the Industrial Internet realizes the integration of IT and OT and the connection of the three systems based on data integration and analysis. As shown in Figure 6, the platform architecture includes three layers: edge layer, PaaS layer and SaaS layer [58].

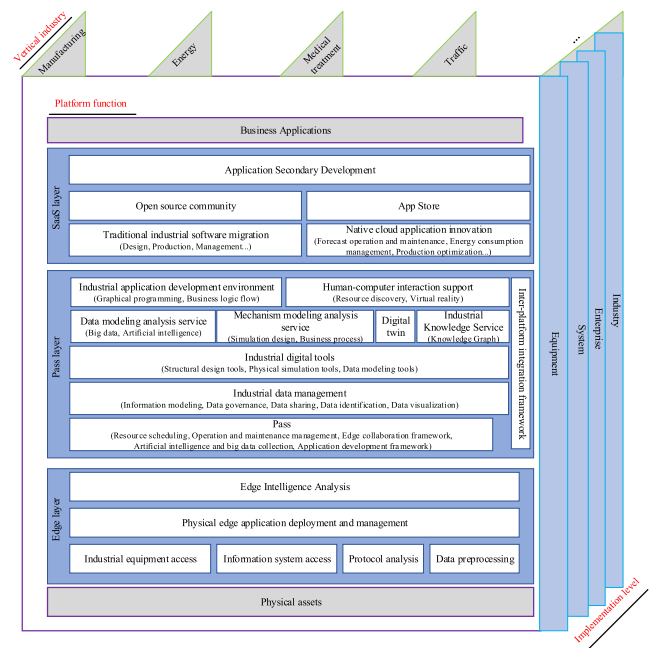


FIGURE 6. Industrial Internet platform architecture [24].

5) FURTHER CONSIDERATION OF REFERENCE ARCHITECTURE OF IIP

Table 1 lists the comparison of reference architectures related to the industrial internet in various countries. It can be seen that the reference architectures proposed by different countries fully consider their national conditions. The IIRA proposed by the United States mainly emphasized its advantages in software services, focused on “soft” services, and

TABLE 1. Comparison of related reference architectures.

Reference architecture	IIRA	RAMI4.0	IVRA	IIA2.0
Organization	IIC	Germany industry 4.0 platform	IVI	AII
Concept	Integration of OT and IT	Focus on the performance improvement of the manufacturing system itself	Industrial Value Chain and Lean production	Integration of new generation of information technology and manufacturing
Classification dimensions	Business, application, function, implementation	Hierarchy, functional categories, lifecycle	Asset, activity and management	Business, function, implementation
Implementation effect	Promote industrial data connectivity, highlight the value of data	Promote the construction of CPS, improve the intelligence level of production system	Promote the value enhancement of industrial chain cooperatively	Data-driven industrial intelligence development based on full interconnection

strived to promote the development of cloud computing, internet, big data and other service in the industrial field. The RAMI4.0 proposed by Germany was based on its strong industrial manufacturing capabilities, mainly emphasizing the “hard” link of the manufacturing system. With the core of Industry 4.0, CPS realizes the organic integration of production system. Japan started from the concept of lean production according to its national conditions, and gave full play to people’s subjective initiative to improve on-site production capacity and achieve profit growth. China seized the opportunity to use information technology to improve industrial quality and efficiency, emphasized the integration of the new generation of information technology and manufacturing, and promoted the development of data-driven industrial intelligence based on full interconnection.

However, it can be seen from the above comparative analysis that due to the late start of China’s industrialization, the manufacturing capacity and internet utilization capacity in the industrial field are relatively weak compared with those of developed countries. Therefore, it is necessary to take into account the development of both soft services and hard links, attach importance to IT/OT integration [25], [26]. A more systematic and comprehensive reference architecture of IIP should be developed from the hardware and software aspects. Meanwhile, the IIP should emphasize the service functions, sort out the platform architecture from the user’s perspective, and simplify the internal complex technical composition.

D. REFERENCE ARCHITECTURE OF IIP

The industry generally believes that the IIP is a multi-layer architecture platform, which needs to connect a large number of industrial equipment, store massive industrial data, and carry industrial applications suitable for a variety of scenarios [27], [28]. In addition, the industry also holds a common opinion that IIP face many challenges in privacy and security-related issues [29], [30]. Currently, most existing reference architectures of IIP are described based on the architecture of the IoT platform, which discuss platform in multiple levels, and define all the services provided at each level according to the business requirements of selected

technologies and services [31]. For example, Atzori *et al.* [32], Domingo [33] and Jia *et al.* [34] described IIP from three-layers namely perception layer, network layer and service layer. Wu *et al.* [35], Yang *et al.* [36] and other researchers believe that the three-layer architecture cannot fully express the entire characteristics and connotation of IIP, thus other levels should be added for expression. Xu *et al.* [37] derived a four-layer architecture including perception layer, network layer, service layer and interface layer from the function perspective. Liu *et al.* [38] presented an architecture including physical layer, transport layer, middleware layer and application layer. Khan *et al.* [39] proposed a five-layer architecture, which includes business layer, application layer, middleware layer, transmission abstraction layer and perception layer. The Industrial Internet Consortium [6] published an IIP framework, which not only provided a description of the overall architecture, but also provided a description of the interface and protocol. In addition, some new architectures with multi-layer structure are emerging, such as the three-layer model including the edge layer, platform layer and enterprise layer [40], [41].

However, it is observed that a unified understanding of IIP and its core functions has not yet been formed. Existing researches described the framework more from the perspective of IT, but lack in-depth consideration from the perspective of industry. Therefore, there are certain limitations, especially in industrial big data management, industrial microservices, industrial APP innovation and ecology.

E. ASSESSMENT FRAMEWORK OF IIP

Conducting the assessment of IIP is a key measure to guide the development of IIP.

At present, the systematic research results on the evaluation of IIP have not yet been formed, but in some specific areas such as the performance and security of IIP, many researchers have conducted research and applications on this. For example, Lee *et al.* [42] proposed a flexible and scalable simulation framework for IIP performance evaluation and conducted experiments in various application scenarios. Vasiljevic and Gardasevic [43] studied the performance

evaluation of the operating system for IIP applications. Ferrari *et al.* [44] evaluated the performance of communication delay in application of IIP. On the basis of studying various maturity model theories, Menon proposed a set of maturity model design ideas for the evaluation of IIP [45]. The alliance of industrial internet released the “Industrial Internet Maturity Assessment” white paper, which puts forward three factors of interconnection, comprehensive integration and data analysis to assess the maturity of IIP [46]. Although the existing researches have carried out preliminary studies on evaluation of IIP and achieved valuable results, there are still some deficiencies. On the one hand, the evaluation object is usually limited to a certain part of IIP development, such as security and capacity, which lacks a comprehensive evaluation. On the other hand, few specific evaluation indicators and evaluation methods are provided.

III. REFERENCE ARCHITECTURE AND MAIN FUNCTIONS OF IIP

A. KEY PROBLEMS FOR IIP TO SOLVE

In Section II, the development history of the industry internet platform is reviewed. We can see that the industrial internet platform is not a certain technical innovation, but an integration innovation of the internet of things, cloud computing, big data and artificial intelligence technology. The IIP provides digital transformation solutions from both sides of IT and OT for industrial enterprises. In our opinion, the emergence of IIP is mainly to solve the inherent problems of traditional industry in five aspects.

1) DIFFICULTY OF INDUSTRIAL DATA COLLECTION

The prominent problem facing the industrial field is the difficulty of industrial data collection, which is mainly caused by the disunity of industrial protocols. Many legacy devices are running based on vendor dependent communication protocol, which follow their own syntaxes. Many kinds of automation manufacturers, research institutions and standardization organizations have launched hundreds of fieldbus protocols, industrial ethernet protocols and industrial wireless protocols around the networking of equipment. Furthermore, field communications are still difficult to exchange data with standard IT systems. As a result, heterogeneous data collected by different equipment systems cannot be compatible, and it is difficult to achieve unified data collection and transmission

2) WEAK ABILITY OF INDUSTRIAL BIG DATA ANALYSIS

At present, a large amount of industrial data is precipitated or disappeared in the enterprise, and the data value has not been effectively played.

On the one hand, there are separate software service providers in each link of production and operation, which leads to serious information isolated island and lack of unified data management. On the other hand, each enterprise information system has already accumulated a large amount of data, but it still lacks intelligent methods to analyze and mine

these data, and fails to transform the data into knowledge to serve the enterprise’s decision-making. In addition, the industrial data usually omits, scatter, or discontinues, resulting in a lot of “dirty data” in industrial field, which need to be cleaned before the development and utilization. At the same time, due to the insufficient precipitation of the collected data, the application value of industrial data analysis cannot reach the expected effect.

3) INSUFFICIENT PRECIPITATION OF INDUSTRIAL MECHANISM MODEL

Nowadays, the prominent problem in the industrial field is the heavy reliance on industry veterans, and there is no stable and solidified industrial mechanism model retained in the enterprise. The reason is that each industry has its own industrial knowledge, and it is a systematic project to package the industrial principle, experience and advanced technology of each industry into a digital model, which needs to continuously invest a lot of resources. In addition, the abstraction of industrial domain knowledge lacks common methods, basic tools, open interfaces and standards, which makes it difficult to split traditional business systems, integrate emerging applications and coordinate cross-domain functions, and results in the obstacles in the accumulation of industrial knowledge and the precipitation of industrial mechanism model.

4) INSUFFICIENT COLLABORATION OF INFORMATION SYSTEM

At present, most of the industrial software deployed in the enterprise has its own data management system, so the namespaces of different enterprise systems are not uniform, and it usually requires the middleware to conduct translation in order to communicate with each other. For example, ERP, MES and SCADA commonly used in factories are usually supplied from different vendors, the collaboration of these systems requires a large amount of labor and material resources to realize business cooperation. In addition, as the integration between IT and OT are not completed, the information network of the enterprise is difficult to extend to the production system, which limits the ability of the IT systems to exchange data with the OT systems.

5) INSUFFICIENT COOPERATION OF THE INDUSTRIAL CHAIN

The current industrial landscape is highly complex and knowledge varies widely. The application innovation mode driven traditionally by a few large enterprises cannot meet the differentiated needs of different enterprises. An open application innovation carrier is urgently needed to lower the threshold of application innovation, and realize the explosive growth of intelligent applications through the open invocation of industrial data, industrial knowledge and platform functions. In addition, with the development of the consumer Internet, new manufacturing models require new methods of business interaction. In order to quickly respond to market changes, parallel organizations and resource coordination in different types of design, production and other fields such

as manufacturing companies, research institutes, and consumers have become more frequent. The enterprise design, production, and management systems need better support business interaction with other enterprises, which needs a new interaction tool to achieve efficient integration between different systems.

B. CORE FUNCTIONS OF IIP

The value of IIP is to promote the ubiquitous connection, dynamic allocation and online sharing of manufacturing resources in the whole society, so as to accelerate enterprises' digital transformation, and construct data-driven manufacturing innovation system. To achieve this target, the IIP should have the following functions:

1) SCHEDULING AND MANAGEMENT OF DISTRIBUTED IT RESOURCE

IIP establishes a heterogeneous resource pool of IT resources and provides efficient scheduling and management services for these resources. By realizing platform-oriented deployment and socialized sharing of IT resources and capabilities, it helps to reduce the enterprise's informatization cost, accelerate the digital transformation, and promote the migration of business to the cloud, so as to provide basic support for the integration and innovative application of OT and IT technology. On the one hand, it is necessary to build distributed cloud infrastructure (IaaS), and realizes pooling and unified management of IT resources through virtualization. On the other hand, scheduling and management services of IT resource should be provided to achieve dynamic and balanced scheduling of cloud infrastructure, and provides services such as flexible capacity expansion, multi-tenant resource isolation and on-demand billing.

2) UBIQUITOUS CONNECTION AND OPTIMAL ALLOCATION OF INDUSTRIAL RESOURCE

IIP comprehensively promotes the digitization and modeling of industrial resources such as "Man, Machine, Material, Method, Environment", and further realize reuse of these resources and capabilities by platform-based deployment, so as to support dynamic allocation of manufacturing resources in whole society. Firstly, edge processing solution should be deployed to connect and extensively gather all kinds of industrial resources, such as specialized technical personnel skills, products and raw materials, equipment and business systems. Secondly, resources from the physical world should be modeled and reconstructed in the information space to form digital twins. Thirdly, the digitized industrial resources should be processed and combined into modular manufacturing capabilities, and services such as dynamic scheduling and optimal allocation of industrial resources should be provided to promote online transactions, allocation and sharing of manufacturing capabilities.

3) MANAGEMENT AND MINING OF INDUSTRIAL BIG DATA

IIP should be capable of gathering, sharing massive industrial data and mining their values, so as to transform the industrial knowledge and experience into reusable models. Firstly, it should provide support for the aggregation, utilization and value mining of massive multi-source and heterogeneous data. Secondly, it should provide intelligent tools to support relevant participants to rapidly encapsulate industrial and IT technologies, knowledge into microservices, and release, call, continuously optimize these microservices. This helps the reuse, propagation, and promotion of knowledge mastered by relevant participants, and helps forming industrial knowledge system.

4) SUPPLY, MANAGEMENT AND ITERATION OF MICROSERVICE

Firstly, IIP should support various microservice component providers to quickly build a series of highly decoupled and reusable industrial microservices of personnel skills, equipment/product, production resources, standard business and industrial environment, as well as IT microservices of database, general algorithm, and middleware. Secondly, it should support the platform construction and operation parties to conduct basic management such as authentication and cancellation of various microservices, and implement quick discovery, orchestration, and invocation of microservices according to APP operation requirements. Thirdly, it should support various types of microservice component providers to conduct continuous and iterative optimization of industrial microservices, IT microservices and micro components based on the usage situation.

5) ENVIRONMENT AND TOOL SERVICES FOR INDUSTRIAL APP LIFECYCLE

IIP should build a developer community to gather all kinds of developers in industry, IT, communication technology and other fields, and provide environment and tool services covering the whole lifecycle of industrial APP to support the development, testing, deployment and operation optimization of various APPs. Specifically, on one hand, it should provide easy-to-use environment and tools of application development and deployment, to fully enable all kinds of developers to quick model and re-package their industrial experience, knowledge and best practices to form a series of APPs with strong practicability. On the other hand, it is necessary to provide industrial APP operation and optimization environment and tools to realize the operation and scheduling of industrial APPs, and conduct iterative optimization of APPs according to the application situation.

6) SECURITY OF IIP

IIP realizes the omni-directional connection of equipment, factories, people and products, so the security and safety system construction must be planned from the perspective of comprehensive protection system. The corresponding

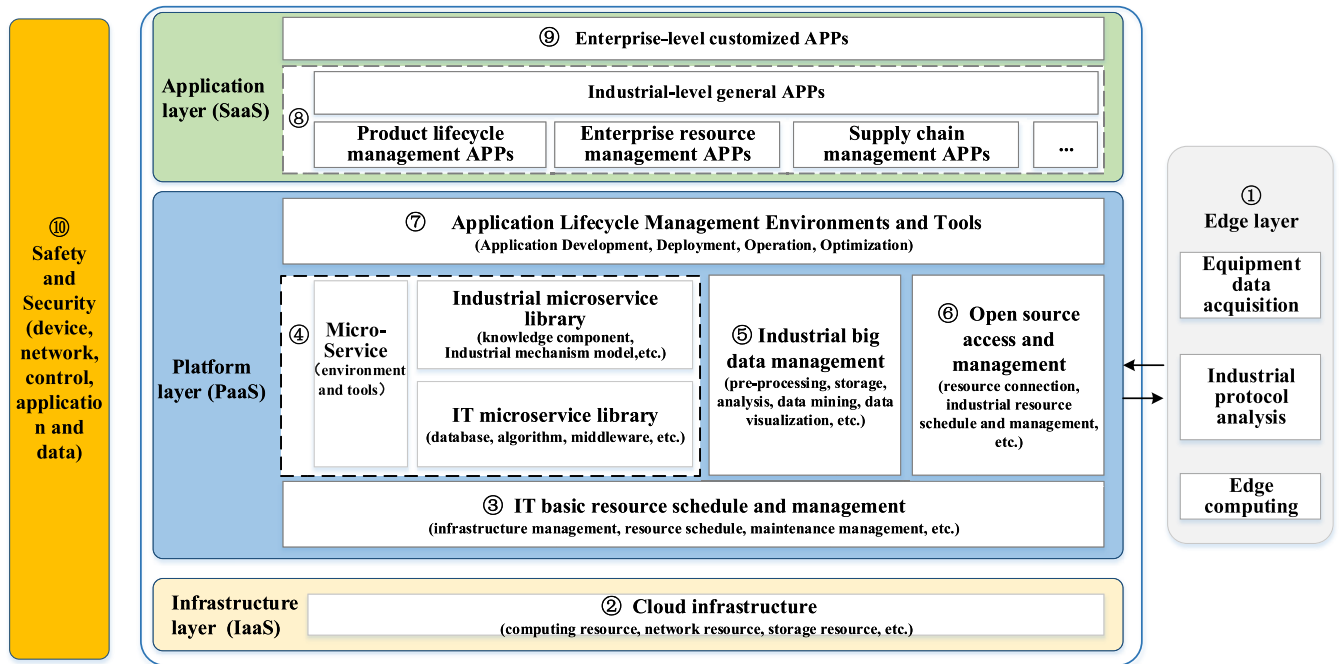


FIGURE 7. Reference architecture of Industrial Internet Platform.

safety protection measures should be implemented at all levels and the security protection of IIP should be realized through the combination of various security technologies and management.

7) INDUSTRIAL ECOLOGY OF IIP

IIP is the key to the innovation and development of the Industrial Internet. The essence is to realize the integration, fusion and innovation of OT and IT capabilities. Based on human knowledge and experience, the digital twins of physical objects are constructed to realize the interconnectivity and interoperation of manufacturing resources, promote the software-oriented, modularized and platform-based manufacturing capacity, so as to support the networked dynamic configuration of the entire society’s manufacturing resources and capabilities, and build a new manufacturing ecology. IIP will help enterprises to transform the mode of value creation from simply supplying products to service-oriented manufacturing that provides “product + service”, realize the integration of industrial production, collaborative manufacturing, service extension and intelligent decision-making, and constantly promote new business forms, new models and new industries, so as to help the manufacturing industry move to a high level in the next stage.

C. REFERENCE ARCHITECTURE OF IIP

Architecture is a high-level abstract framework used to describe the system composition and the relationship between the components. Establishing IIP reference architecture is an important way to unify the cognition of all sectors of

society. As the product of the integration of new generation information technology and manufacturing industry, IIP is an open and professional service platform for digital transformation and innovation of manufacturing industry. It helps to accelerate the fundamental transformation of the innovation system and development mode of manufacturing industry by realizing ubiquitous connection, flexible supply and efficient allocation of all kinds of industrial factors. Building a fully functional IIP usually requires the full participation of industrial enterprises, ICT enterprises, solution providers and other parties. In order to fully describe the composition of IIP and relevant subjects involved in platform construction and operation, this study adopts a multi-layer description method to build the basic architecture of industrial internet platform. As shown in Figure 7, it consists of edge layer, infrastructure layer (IaaS), platform layer (PaaS), application layer (SaaS), safety and security.

1) EDGE LAYER

As shown in Figure 8, the edge layer constructs the data foundation of the IIP through large-scale data acquisition, as well as the protocol transformation and edge processing of

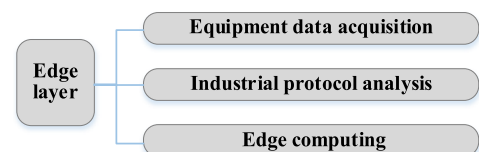


FIGURE 8. Edge Layer.

heterogeneous data. Firstly, the edge layer collects massive amounts of data by accessing different devices, systems and products. Then, the protocol transformation technology is used to realize the integration of multi-source heterogeneous data. Finally, edge computing devices are used to aggregate basic data and integrate data into cloud platforms.

2) INFRASTRUCTURE LAYER (IaaS)

Infrastructure layer (IaaS), see function block (2) in Figure 7, is the operation foundation of IIP, which provides virtualized infrastructure resources, mainly including computing, storage and network resources.

As shown in Figure 9, the virtualized infrastructure resources provided by IaaS is essential for the function operation, capacity building and service supply of platform layer (PaaS) and application layer (SaaS), and usually supplied by IT infrastructure providers. Affected by the development of consumer internet, IaaS has relatively high maturity in technology and application, and technological innovation is iterated rapidly. Amazon, Microsoft, Alibaba, Huawei and other cloud service providers can provide mature IaaS solutions.

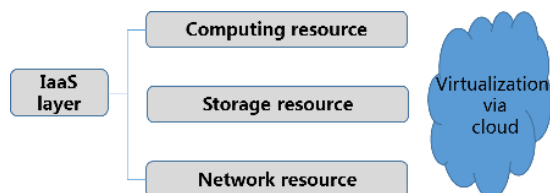


FIGURE 9. IaaS Layer.

3) PLATFORM LAYER (PaaS)

PaaS layer plays a role like “operating system”, relying on modular microservices, powerful data processing ability, efficient access and management of social resource, and open APP development environment & tools. As shown in Figure 10, its function includes following aspects: IT basic resources schedule(see function block (3) in Figure 7), microservice environment, tools and library (function block (4)), industrial big data management (function block (5)), open sources access and management (function block (6)) and applications lifecycle management environments and tools (function block (7)).

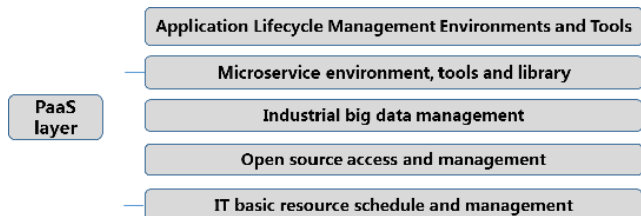


FIGURE 10. PaaS Layer.

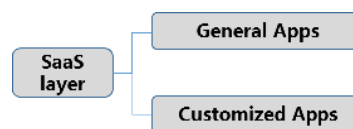


FIGURE 11. SaaS Layer.

PaaS layer is usually built by platform constructors, microservice component providers, and edge solution providers. Its construction not only requires deep accumulation of manufacturing technology, but also requires the ability to transform industrial knowledge into digital, modular and software-based industrial mechanism models, which is the key to IIP construction. Currently, manufacturing companies with a high level of informatization and leading ICT companies are the main providers of PaaS technology.

4) APPLICATION LAYER (SaaS)

The application layer directly reflects the value of IIP. It can stimulate the entire society and use the resources and functions provided by IIP to transform business models, technologies, data and resources into a series of platform-based industrial APPs. This can largely realize the reuse and innovation of industrial knowledge. Various of APPs are provided in SaaS layer, which can be mainly classified into two categories, i.e. general APPs (see block (8) in Figure 7) and customized APPs (see block (9) in Figure 7).

The large-scale application of various industrial APPs is the key to promote the optimal allocation of social resources and accelerate the construction of platform-based open innovation ecology. At present, the development potential of SaaS has not been fully realized due to the insufficient capacity of PaaS, but a batch of industrial APPs with obvious application effects have emerged in certain fields or specific scenarios.

5) SAFETY AND SECURITY

Information security, network security and industrial control security are important aspects of the safe and security of IIP, so safety and security of IIP mainly carry out comprehensive security protection from the edge layer, infrastructure layer, platform layer and application layer to enhance the security capability of equipment, network, data and application, see function block 10 in Figure 7.

The security systems effectively identify, resist and resolve security risks, and build a secure and trusted environment for the development of IIP. Specific protective measures include intrusion detection, behavior analysis, security audit, disaster recovery backup, situational awareness and other security technologies, so as to realize closed-loop management of monitoring, alarm, disposal, traceability, recovery and inspection of industrial Internet security.

As shown in Figure 12, the reference architecture of IIP is further refined and the main construction subjects are described to form a more explicit architecture and innovation ecology of the IIP.

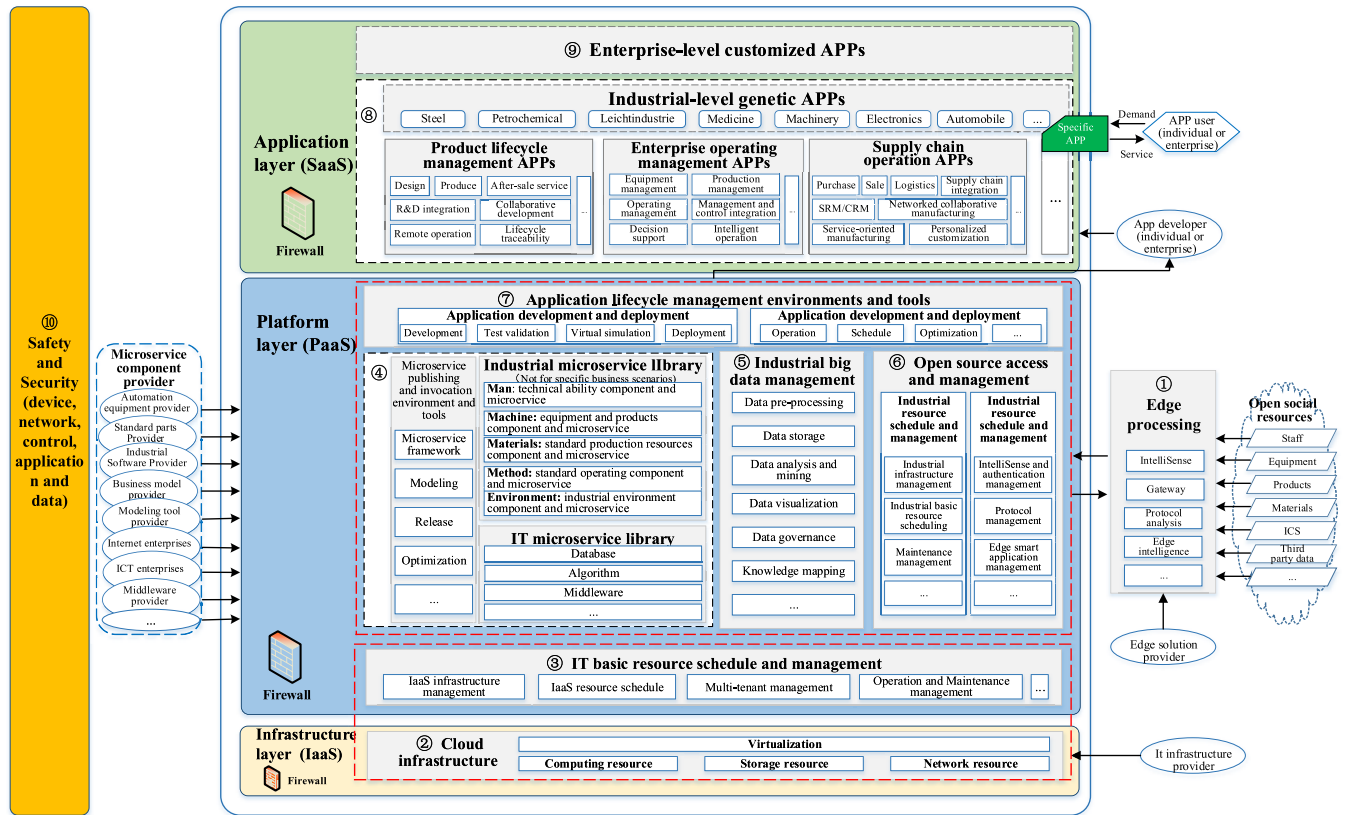


FIGURE 12. Content details of reference architecture of IIP.

D. INDUSTRY CUSTOMIZED ARCHITECTURE

Taking the electronic information industry and the steel industry as examples, specific industry architectures are derived from these industries through the general architecture, which illustrates the practical application value of the IIP architecture. When the IIP proposed in this study is applied to a certain industry, industry knowledge base, industry mechanism models and industrial APPs should be established according to industry characteristics.

1) CUSTOMIZED ARCHITECTURE OF THE ELECTRONIC INFORMATION INDUSTRY

As shown in Figure 13, it illustrates the application of the IIP reference architecture in the electronic information industry. The edge layer and IaaS layer of different industries are much similar, and the industry attributes are mainly reflected in the PaaS layer and SaaS layer. In the field of electronic information industry, the following will describe the customized reference architecture IIP in detail as below.

a) Edge Layer: It includes devices with edge computing capabilities, such as smart sensors, industrial gateways, etc., mainly performing edge computing, protocol analysis and other operations.

b) IaaS Layer: Convergence of various virtualized cloud infrastructures, including computing resources, network resources, and storage resources.

c) PaaS Layer: The difference of the PaaS layer in different industries is mainly reflected in the industrial mechanism model. The Industrial knowledge base of the electronic information industry contains experience related to the manufacturing processes, product testing, electronic manufacturing process, monitoring classification, etc. Industrial mechanism model contains relevant models such as intelligent control of equipment model, enterprise production model, product quality management model, supply chain coordination model.

d) SaaS Layer: SaaS layers in different industries are different. Although information systems, such as ERP, MES, and SCM, are widely used in different industries, their functional module settings are different. The ERP of the electronic information industry generally contains functional modules related to quality management and operation management, including product quality management, enterprise operation management, integrated marketing, etc. MES usually contains functional modules related to scheduling, logistics and equipment, including production scheduling, material management, etc. In addition, the SaaS layer contains some customized APPs, such as pipeline monitoring APPs and process improvement APPs.

2) CUSTOMIZED ARCHITECTURE OF THE STEEL INDUSTRY

As shown in Figure 14, it illustrates the application of the IIP reference architecture in the steel industry. The following will

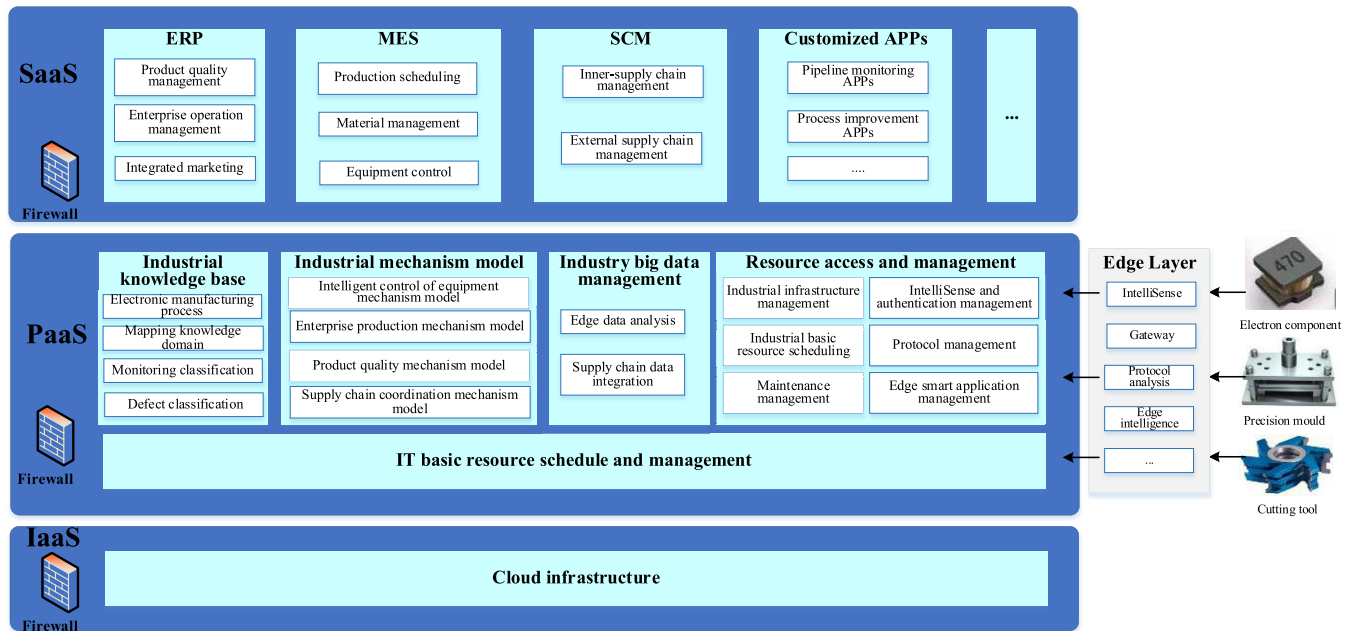


FIGURE 13. Customized architecture of IIP in the electronic information industry.

describe the customized reference architecture IIP in detail as below.

a) Edge Layer: It includes devices with edge computing capabilities, such as smart sensors, gateways, etc., mainly performing edge computing, protocol analysis and other operations.

b)IaaS Layer: Convergence of various virtualized cloud infrastructures, including computing, network and storage resources.

c)PaaS Layer: The industrial knowledge base of the steel industry usually contains experience in the smelting process and process control. Industrial mechanism models generally include production process models, energy conservation and consumption reduction models, etc.

d)SaaS Layer: The ERP of steel industry usually contains functional modules related to assets, finance, and quality, including enterprise asset management, energy consumption management, sewage management. MES usually contains functional modules related to production line, operation and maintenance, inventory, etc. In addition, the SaaS layer of the steel industry includes some customized enterprise-specific APPs, such as furnace erosion monitoring APP and cooling stove monitoring APP.

IV. ASSESSMENT FRAMEWORK OF IIP

The construction of IIP is a complex system-engineering project. Although various IIPs are rising rapidly in the world, they are still in the initial stage of exploration. From exploration to improvement, industrial Internet platform still needs to go through a process of dynamic optimization and iterative evolution. Although the reference architecture of IIP defines a general framework and provides a reference for platform

construction. However, the capacity, ecology and business model construction of the IIP cannot be fully reflected in the reference architecture. Therefore, platform-oriented assessment system can better guide the construction of IIP. Conducting IIP assessment and diagnosis can help accurately locating the weak link of platform construction, and clarifying the direction of improvement, thus guidance on the development of IIP can be fulfilled. Based on the reference architecture and main functions of IIP proposed in Section III, this section further proposes an assessment system to guide the development of IIP.

A. BASIC FRAMEWORK FOR IIP ASSESSMENT

In order to effectively conduct IIP construction, we should take value and benefit promotion as orientation, capability of platform empowerment as core, and the solidness of platform foundation as premise. In order to guide the continuous improvement of platform construction capacity and operation level, and accelerates the construction of platform-based open ecology, this study constructs an assessment framework from 3 dimensions, foundation, key capability, value and benefit, and 9 sub-aspects in specific, as shown in Figure 15 [11], [47]–[49].

The *platforms' foundation* includes 3 aspects, namely strategic positioning, talent guarantee and security system. It synthetically judges the suitability of platform's basic condition by evaluating the situation of IIP's strategic planning, talent structure, fund guarantee, and safety system construction. *Platforms' key capability* evaluates IIP's key capability from 4 aspects, namely cloud-based resource management and scheduling of IT and manufacturing resources, management and mining of industrial big data, deployment and

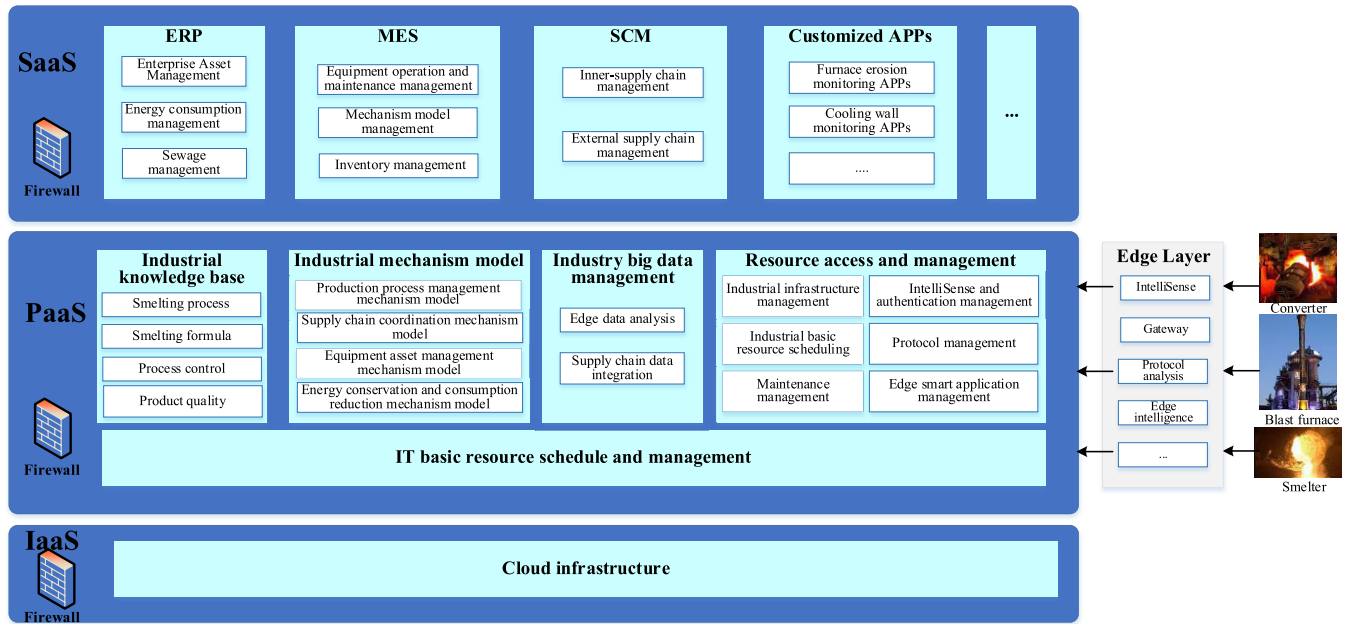


FIGURE 14. Customized architecture of IIP in the steel industry.

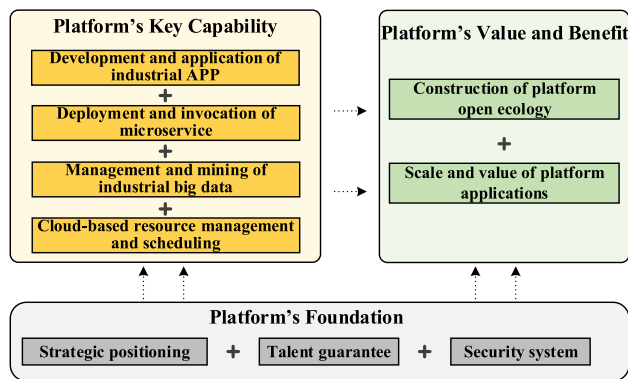


FIGURE 15. Assessment framework of IIP.

invocation of microservice, and development and application of industrial APP. *Platform's value and benefit* proceeds from 2 aspects, namely scale and value of platform applications, construction of platform open ecology, to evaluate the value and benefit created by the IIP.

B. ASSESSMENT INDICATORS OF IIP'S FOUNDATION

The continuous optimization and iterative evolution of IIP relies on several important prerequisite, including determining a reasonable platform development orientation, building up long-term development planning, establishing sustainable funds input mechanism and professional talent team, and constructing solid information security system. Therefore, the main evaluation content of platform's foundation is designed around several perspectives, including "strategy, talent, fund, security". Specific indicators and assessment essentials are shown in Table 2, in which:

1) *Strategic positioning.* Firstly, by investigating the mission and vision of the platform, it evaluates the suitability of platform's general development positioning, and whether it can provide good services for enterprise digital transformation and innovative development. Secondly, it evaluates whether the platform have long-term planning and reasonable evolution path that matches the development direction of the platform. Thirdly, by investigating funds input mode and construction of sustainable funding mechanisms, it evaluates whether the funds input can meet the long-term development needs of the platform.

2) *Talent guarantee.* It evaluates whether the talent guarantee can meet the sustainable development needs of the platform, mainly through investigating the organizational structure, the talents scale and composition of platform construction and operation.

3) *Security system.* It synthetically evaluates the security guarantee capability of the platform such as infrastructure security, network security, data security, and application security, by investigating security technology means adoption, and security mechanism construction of the platform, and examine the practical capability of the platform's resistance to cyber risks by evaluating the economic losses caused by cyber risks [13], [50], [51].

C. ASSESSMENT INDICATORS OF PLATFORM'S KEY CAPABILITY

The assessment indicators and evaluation essentials constructed around platform's key capability above are shown in Table 3, in which:

1) *Cloud-based management and scheduling of resources.* On one hand, it synthetically evaluates the

TABLE 2. Assessment indicators and essentials of platform foundation.

Second Grade Indicator	Third Grade Indicator	Evaluation Content	Evaluation Essential	
Strategic positioning	Mission of platform	Strategic positioning	• Whether it can match with the current situation and trend of its industry, adapt to the development status and trend of new generation of information technology, and agree with platform’s competitive advantages needs.	
		Strategic implementation	• The matching degree between the main functional business of the platform and its strategy. • The construction of strategic control mechanisms, such as strategic goal decomposition mechanism, tracking and monitoring mechanism, continuous improvement mechanism etc.	
	Evolution path of platform	Planning formulation	• The formulation of platform planning, whether a special strategy has been formulated, and the development path of the platform has been provided.	
		Planning implementation	• The feasibility of platform planning, whether the planning tasks have been decomposed, and the tracking & feedback mechanism, assessment system & requirements have been constructed. • The actual implementation of the planning, whether the phased goals have been achieved, and the implementation process has been continuously controlled.	
	Funds input of platform	Input mechanism	• The formulation of funds input plan, whether the fund source and using plan have been explicit.	
		Input situation	• The situation of funds input, including the total scale of invested funds and future plans.	
Talent guarantee	Organizational structure	Construction subject	• Whether the platform constructor has necessary industry technology and IT technology capabilities.	
		Organizational structure	• Whether the platform constructor has built organizational structure that can meet the needs of networking and platform-based operation. • The number of professionals engaged in the platform construction and operation.	
	Talent system	Talent structure	• The coverage of professionals’ fields, including number of personnel mastered ICT knowledge and skill, number of personnel mastered professional knowledge and skill of specific industrial fields, and number of personnel responsible for the construction and promotion of the platform ecology.	
		Personnel empowerment	• Whether necessary empowerment measures have been taken to insure that the staff’s abilities can match with the platform’s development. • Whether effective measures have been taken to insure that professional talents can be trained and recruited quickly to meet dynamic development needs of the platform.	
	Security system	Security mechanism	Security mechanism	• Whether management system of information security has been built, and hidden dangers can be controlled. • Whether effective countermeasures of information security accident have been constructed.
			Economic impact of cyber risks	• Economic losses due to IIP network risks
	Security technology	Security technology	• The adoption of technologies for networking security, data security, industrial equipment access security, et al.	

capability and level of cloud-based management and scheduling of IT resources, by assessing the access method, access speed and capacity expansion ability of IT resources. On the other hand, it synthetically evaluates the connectivity ability and level of manufacturing resources including “Man, Machine, Material, Method and Environment”, by assessing the rationality and validity of resource connecting and acquisition means such as edge processing, protocol compatibility and network transmission, and by assessing the access scope, scale, type and speed of manufacturing resources as well.

2) Management and mining of industrial big data. Firstly, it evaluates the platform’s big data acquisition level, from aspects of data resources connecting, edge data processing, communication protocol support and so on. Secondly, it evaluates the platform’s ability of big data processing and data analysis, by assessing the conversion, cleaning, hierarchical storage and visualization processing level of massive multi-source heterogeneous data, and by assessing the diversity and practicability of the analysis algorithm adopted. Thirdly, it evaluates the platform’s data modeling level by assessing the digitization and modeling degree of industrial mechanism, experts’ experience, decision rules, and the scale and type of mechanism models as well.

3) Microservice deployment and invocation. Firstly, it evaluates the development environment and tool service

level, by assessing the basic microservice management capability such as microservice authentication and cancellation, and by assessing the capability of quick discovery, orchestration, and invocation of microservices. Secondly, it evaluates the supply capability of IT microservices through the types, development speed, usage situation of existing IT microservice. Thirdly, it evaluates the supply capability of industrial microservices, through types and usage situation of industrial microservices around “Man, Machine, Material, Method and Environment”.

4) Industrial APP development and application. Evaluating the capability and level of industrial APP development and utilization, through assessing the construction of lifecycle development environment and tool, the scale and composition of different type of industrial APPs, the usage of industrial APP (e.g. user number, regional and industrial distribution), and developer community construction situation like functions of the community and composition of resident developers.

D. ASSESSMENT INDICATORS OF PLATFORM’S VALUE AND BENEFIT

The core value of IIP can only play its full role, by building up platform-based open cooperative ecology, realizing

TABLE 3. Assessment indicators and essentials of platform key capability.

Second Grade Indicator	Third Grade Indicator	Evaluation Content	Evaluation Essential	
Cloud-based management and scheduling of resources	Cloud-based management and scheduling of IT resources	Computing performance	<ul style="list-style-type: none"> Average speed and utilization ratio of the computing resource. 	
		Cloud-based management of computing resource	<ul style="list-style-type: none"> The functional realization of cloud-based management and scheduling for computing resource, like whether distributed parallel computation, dynamic allocation and on-demand billing can be supported. Elastic expansion of computing resource, whether dynamic and flexible expansion capacity is realized. Whether it can meet the needs for daily operation and dynamic business expansion. 	
		Storage performance	<ul style="list-style-type: none"> Average reading and writing speed, utilization ratio of the storage resource. 	
	Connection and optimal allocation of manufacturing resources	Type and number	Cloud-based management of storage resource	<ul style="list-style-type: none"> The realization of cloud-based management and scheduling for storage resource, like whether distributed parallel computation, dynamic allocation and on-demand billing can be supported. Whether isolation and sharing of storage resource can meet the needs of security and openness meanwhile. Whether the storage resource can meet the needs for daily operation and dynamic business expansion.
			Network performance	<ul style="list-style-type: none"> The performance of network resources, such as the maximum number of concurrent access that can support. Whether it can support multiple access to meet the needs of reliability, scalability and security. Whether the network resources have flexible elastic expansion capability. Whether it can overall meet the needs for daily business operation and dynamic business expansion.
			Cloud-based management of network resource	<ul style="list-style-type: none"> The types of manufacturing resources accessed to the platform. The number and types of industrial equipment accessed to the platform. The number and type of industrial software accessed to the platform.
Management and mining of industrial big data	Data acquisition	Resource distribution	<ul style="list-style-type: none"> Regional and industrial distribution of accessed resources. 	
		Edge data processing	<ul style="list-style-type: none"> Supported functions of edge processing, such as data acquisition, intelligent analysis and control, etc. Performance of edge processing, such as the minimum response delay that it can support. Connected number of edge computing application nodes. 	
	Data processing and analysis	Gateway and protocol	<ul style="list-style-type: none"> Types of compatible communication protocols. 	
		Functional status	<ul style="list-style-type: none"> Supported big data management functions, such as storage, analysis and mining, visualization, etc. Whether the data storage strategy can meet the requirements of data access and processing. Whether it can support the conversion of heterogeneous data. 	
		Data processing level	<ul style="list-style-type: none"> The overall level of data processing, magnitude of data storage, data analysis speed, conversion efficiency of heterogeneous data, proportion of visualized data, etc. 	
		Intelligent analysis capability	<ul style="list-style-type: none"> The types of intelligent analysis algorithms the platform contains, such as advanced modeling analysis, personalized recommendation, etc. The construction capability of industrial knowledge (e.g. decision rules, business characteristic models), based on the intelligent analytical means including human-computer interaction and unsupervised learning. 	
Data modeling	Scale and composition	<ul style="list-style-type: none"> The number of mechanism models (e.g. basic theoretical model of specific industry, business logic model, process model, fault model) based on the intelligent analysis of big data. The proportion of active mechanism models. Number of covered industries of mechanism models based on the intelligent analysis of big data. 		
	Usage situation	<ul style="list-style-type: none"> The usage of mechanism models, such as the monthly average calls in the last year. 		
Microservice deployment and invocation	Development environment and tools of microservice	Scheduling and management tools of IT resources	<ul style="list-style-type: none"> Supported functions of IT resource scheduling and management tools, such as resource deployment, identity authentication, condition monitoring, multi-tenant management and billing, analysis report, etc. The suitability of IT resources scheduling mode and strategy, whether reasonable scheduling strategies are adopted to meet the requirements of resource utilization ratio and load balancing. 	
		Scheduling and management tools of industrial resources	<ul style="list-style-type: none"> Supported functions of industrial resource scheduling and management tools, such as resource access authentication, condition monitoring, dynamic scheduling, transaction and billing management, etc. The suitability of industrial resources scheduling mode and strategy, whether it adopts reasonable scheduling strategies to meet the needs like resource utilization ratio, etc. 	
	IT microservice	Number and usage of IT microservice	Development environment and tools of microservice	<ul style="list-style-type: none"> Supported functions of microservice publishing and invocation environment and tools, whether it can support online operation such as the development, testing, release, invocation and optimization.
			Industrial microservice	<ul style="list-style-type: none"> The type and number of IT microservices. The increase of IT microservice, such as the monthly average increased number of new IT microservices. The active degree of IT microservice, such as monthly average increased invocation times.
Industrial APP development and application	Development environment and tools of industrial APP	Functions of development environment	<ul style="list-style-type: none"> The type and number of industrial microservices. The increase of industrial microservice, such as the monthly average increased number of new microservices. The active degree of industrial microservice, such as the monthly average invocation times, etc. 	
			<ul style="list-style-type: none"> Realization of lifecycle management of applications, whether it covers development, test verification, virtual simulation, implementation and deployment, operation and scheduling, optimization, etc. The convenience of application development, like whether visual dragging development can be supported. The realization for multilingual development. 	
	Scale and composition of industrial APP	Total scale of the industrial APP	<ul style="list-style-type: none"> The total number of industrial APPs deployed. The functional diversity of industrial APPs deployed. 	
		Excellent industrial APP	<ul style="list-style-type: none"> The number of excellent industrial APPs (the applications those have gained large-scale application and achieved effective results). The types of application scenarios that served by the excellent industrial APPs. 	
	Usage of industrial APP	User number	<ul style="list-style-type: none"> The total user number of platform's industrial APPs. The average user number of platform's excellent industrial APPs. The active degree of APPs, such as number of monthly new APP users, number of daily active APP users. 	
			User distribution	<ul style="list-style-type: none"> The range of regions covered by APP users. The industries covered by APP users.
Developer community	Developer community functions	<ul style="list-style-type: none"> Whether the platform has constructed developer community. Whether the developer community has good functions, such as the publishing and acquisition of APP needs, the development, testing and publishing of APP, the knowledge and resources sharing, etc. 		
		Scale and composition of developers	<ul style="list-style-type: none"> The number of developer accounts registered. The increase of registered developers, such as the average number of new developers registered last year. The proportion of active developers. The number of senior developers. 	

large-scale application, and effectively serving the digitalization and innovative development of enterprises. Therefore, this study constructs the assessment indicators and

assessment essentials of platform's value and benefit from 2 aspects, including platform application and open ecology, as shown in Table 4, in which:

TABLE 4. Assessment indicators and essentials of platform value and benefit.

Second Grade Indicator	Third Grade Indicator	Evaluation Content	Evaluation Essential
Platform application	Scale of application	User number	<ul style="list-style-type: none"> The total number of platform users. The increase of platform users, such as the monthly average user number increased in the last year.
		User distribution	<ul style="list-style-type: none"> The regional and industrial distribution of platform users.
		Long-term served industry and scenarios	<ul style="list-style-type: none"> The number of long-term served industries. The number of long-term served industrial scenarios.
	Value of application	Mode innovation	<ul style="list-style-type: none"> The innovation of production and service model driven by the application of the platform, such as networked collaborative development, personalized customization, service-oriented manufacturing, industry chain finance, etc.
		Industry cultivation	<ul style="list-style-type: none"> The cultivation of new industries driven by the application of the platform, such as the edge computing, microservice, industrial APP, data trading and other industries.
		Economic and social benefits	<ul style="list-style-type: none"> The operation income and its increase, and the transaction scale and its increase of the platform. The improvement of utilization rate, operation and maintenance cost, energy consumption and security performance of industrial equipment connected to the platform. The number of newly increased employment driven by the construction and operation of the platform. Social contribution rate of the platform.
Open ecology	Open and sharing of data	Scale and composition of open data	<ul style="list-style-type: none"> The volume of open data, and its proportion to the total stored data on the platform. The increase of open data, such as the monthly average growth rate of the open data in the last year. The diversity and importance of open data.
		Access and usage of open data	<ul style="list-style-type: none"> The access way for users to get the open data, such as online trading, free access, strategic cooperation, etc. The number and type of users using open data.
	Platform-based operation model	Benefit-share mechanism	<ul style="list-style-type: none"> Whether the platform has constructed an appropriate benefit-sharing mechanism, which is favorable to the sustainable development of the platform. Common benefit-sharing mechanisms including distributing revenues according to the actual usage amount of services for providers of resources, microservice components and APP, distributing revenues according to capital input amount, distributing revenues according to a fixed proportion as agreed, and so on.
	Innovation ecology construction	Opening and co-construction	<ul style="list-style-type: none"> Whether the construction and operation of the platform have incorporated necessary subjects such as IT infrastructure providers, microservice providers, industrial resource owners, edge solution providers, industrial APP developers, etc.
Cross-platform invocation		<ul style="list-style-type: none"> Supporting status of cross-platform invocation function, whether cross-platform migration of shared data, cross-platform invocation of industrial microservice or industrial APP can be realized. 	

1) **Platform application.** On one hand, it evaluates the scale of platform application, through the platform user number, increase and distribution of platform users, status of long-term served industries and industrial scenarios. On the other hand, it evaluates the value of platform application, through the platform profit gained, user profit gained, the model innovation of production and service, the cultivation of new industry.

2) **Open ecology.** Firstly, it evaluates the open and sharing capability of platform’s data, through the situation of “data supply” such as the scale, type, composition and timeliness of open data, and through the situation of “data utilization” such as the total user number and third-party user number of open data. Secondly, it evaluates the construction of platform operation mode, by assessing the openness of platform technology and the methods of benefit-sharing. Thirdly, it evaluates the innovation ecology construction of the platform that related parties participated in.

E. ASSESSMENT METHOD AND PROCESS

Government departments, industry organizations, platform construction enterprises, third-party organizations and others can conduct the assessment work based on the proposed assessment system to clarify the status quo of the platform

and find out the weak links, so as to promote platform construction in a more targeted way.

1) DATA COLLECTION

There are quantitative and qualitative indicators in the assessment system, so different means should be used to collect data. For quantitative ones, each assessment item can be scored through interview, on-site collection, questionnaire, etc. For qualitative ones, expert teams can be built to conduct information reviews and field assessment. The team should be made up of experts from IT industry, manufacturing industry, etc. Each assessment item can be scored through comprehensive evaluation and analysis according to platform function demonstration, as well as the communication and interview with professionals of platform constructors.

2) INDICATOR WEIGHT SETTING

The importance and influence of each indicator should be comprehensively considered before assessment. Analytic hierarchy process and other methods can be adopted to set the indicator weight value. The importance of the same grade indicators should be quantified and compared, and the weight value of each indicator should be determined between (0, 1).

For example, a certain indicator has n sub-indicators, and the weight of each sub-indicator is W_i , $0 < W_i \leq 1$ and $\sum W_i = 1$.

Analytic Hierarchy Process (AHP) is used to hierarchize the problems to be analyzed, and the assessment indicators are aggregated at different layers to form a multi-layer analysis structure model. Based on the hierarchical structure model, the relative importance of all indicators is ranked and the weights are finally determined [53]–[56].

a: BUILDING THE HIERARCHICAL MODEL

As shown in Figure 16, the assessment indicators proposed in this study can be divided into three layers, including 3 elements in the first layer, 9 elements in the second layer, and 24 elements in the third layer.

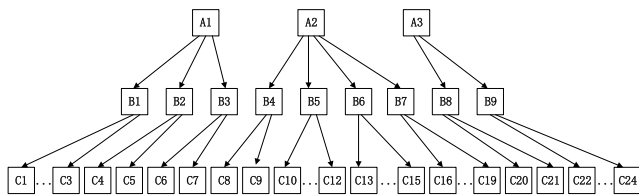


FIGURE 16. Hierarchical Model.

b: CONSTRUCTING THE FEATURE MATRIX

The expert’s experience is used to compare the importance of the elements in each layer, and the feature matrix of this layer is constructed. The feature matrix can be adjusted according to the consistency test.

The first layer(A) is to construct a 3*3 feature matrix. The second layer(B) is to construct 3 matrices, one is a 3*3 feature matrix corresponding to [B1, B2, B3], the other is a 4*4 feature matrix corresponding to [B4,B5,B6,B7], and the last is a 2*2 feature matrix corresponding to [B8,B9]. The third Layer (C) is to construct 9 matrices according to the above method.

c: HIERARCHICAL ORDER AND CONSISTENCY CHECK

After normalization, the eigenvector corresponding to the maximum eigenvalue λ_{max} is recorded as ω . Then, the element of ω is the ranking weight of the element of a certain layer relative to the corresponding element of the upper layer.

In order to ensure the quality of the constructed feature matrix, consistency check need to be implemented. The consistency ratio is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

When the order n of the matrix is above 3, the above consistency ratio needs to be corrected by the correction factor RI . The value of the correction factor RI can be found in Table 5.

TABLE 5. Value table of correction factor RI.

n	1	2	3	4	5
RI	0	0	0.58	0.90	1.12

The correction formula for the consistency ratio is defined as:

$$CR = CI/RI$$

When $CR < 0.1$, the inconsistency of the feature matrix is satisfactory within the allowable range. Then, the normalized feature vector ω can be used as the weight vector. Otherwise, the importance of pairwise comparison in the feature matrix needs to be adjusted, and the pairwise comparison feature matrix needs to be reconstructed.

Since the assessment system contains three layers of indicators, from the first layer to the third layer, the consistency check is performed on each feature matrix.

d: HIERARCHICAL TOTAL SORTING AND CONSISTENCY CHECK

After the weight of each element relative to the corresponding upper element is calculated in the order from the highest layer to the lowest layer, then we can obtain the weights of all elements in each layer for the target problem.

The weight of element A_i for the target problem is recorded as a_i ($i = 1,2,3$), the weight of B_j for the upper element A_i is recorded as b_{ij} ($j = 1,2,...,9$), and the weight of C_k for the upper element B_j is recorded as c_{jk} ($j = 1,2,...,24$). The weights of B_j and C_k not directly related for the upper elements are set to 0. As shown in Table 5, the weight of each element in layer B is $\sum_{i=1}^3 a_i b_{ij}$, the weight of each element in layer C is

$$\sum_{i=1}^3 a_i \sum_{j=1}^9 b_{ij} c_{jk}.$$

3) STANDARDIZATION OF COLLECTED DATA

For quantitative data in questionnaire, it may be impossible to conduct unified calculation and analysis due to different sources and different units. The range standardization method can be used to unify the quantitative data, as shown in formula (1):

$$X_i = \frac{V_i - V_{min}}{V_{max} - V_{min}} \times 100 \tag{1}$$

where, V_i is the actual value of the assessment item, V_{min} and V_{max} are the minimum and maximum thresholds of the item. The score X_i is the value within the range of [0,100].

For qualitative data in questionnaire, they are appeared as choice questions in the questionnaire. Different options correspond to different scores, and the scores are also in the range of (0, 100).

4) WEIGHTED TOTAL SCORES

For each evaluated platform, the scores of the indicators from the first grade to the third grade can be calculated by weighting the scores of the indicators of the lower grade, and the total scores can be calculated by weighting the scores of the indicators of the first grade. Suppose the sub-indicator score of an indicator is $\{X_i | i = 1,2,...,n\}$, then the scoring

TABLE 6. Weights of elements.

Element in layer B	Weights	Element in layer C	Weights	Element in layer C	Weights
B1	a_1b_{11}	C1	$a_1b_{11}c_{11}$	C13	$a_2b_{26}c_{613}$
B2	a_1b_{12}	C2	$a_1b_{11}c_{12}$	C14	$a_2b_{26}c_{614}$
B3	a_1b_{13}	C3	$a_1b_{11}c_{13}$	C15	$a_2b_{26}c_{615}$
B4	a_2b_{24}	C4	$a_1b_{12}c_{24}$	C16	$a_2b_{27}c_{716}$
B5	a_2b_{25}	C5	$a_1b_{12}c_{25}$	C17	$a_2b_{27}c_{717}$
B6	a_2b_{26}	C6	$a_1b_{13}c_{36}$	C18	$a_2b_{27}c_{718}$
B7	a_2b_{27}	C7	$a_1b_{13}c_{37}$	C19	$a_2b_{27}c_{719}$
B8	a_3b_{38}	C8	$a_2b_{24}c_{48}$	C20	$a_3b_{38}c_{820}$
B9	a_3b_{39}	C9	$a_2b_{24}c_{49}$	C21	$a_3b_{38}c_{821}$
		C10	$a_2b_{25}c_{510}$	C22	$a_3b_{39}c_{922}$
		C11	$a_2b_{25}c_{511}$	C23	$a_3b_{39}c_{923}$
		C12	$a_2b_{25}c_{512}$	C24	$a_3b_{39}c_{924}$

method of this indicator is shown in formula (2):

$$Y = \frac{\sum_{i=1}^n X_i \times W_i}{\sum_{i=1}^n W_i} \quad (i = 1, 2, \dots, n) \quad (2)$$

5) APPLICATION OF ASSESSMENT DATA AND RESULT

Various kinds of data analysis methods can be further adapted to mine deeply based on the collected data and the scoring results. According to the need, comparative analysis or correlation analysis among different indicators can be adopt to precisely locate status, problems and trends of IIP, and then determine priority areas for construction and development, and then form feasible development paths and implementation plans.

V. PRACTICAL IMPLEMENTATION OF ASSESSMENT FRAMEWORK OF IIP

With the reference to the architectures of Industry 4.0, CPS, intelligent manufacturing and industrial internet, the reference architecture of IIP is proposed by summarizing and refining the structure, elements and models of many excellent industrial internet platforms in different industries and enterprises at home and abroad [59]–[61]. We hope to share and promote the experience of excellent platforms, guide the construction of new platforms, and lead the continuous optimization of existing platforms. Therefore, the architectures of many existing platforms are consistent with the architecture proposed in this study, such as UNIPower, Cloudiip and Rootcloud, etc.

The proposed assessment system is not only applicable to the assessment of IIPs whose functional design conforms to the IIP reference architecture proposed in this study, but also to those whose architecture does not conform to our research. Using the assessment system, we can accurately locate the weakness of platform’s composition, clarify the direction of improvement, and guide the development of IIP.

A. CASE STUDY

We have established an IIP assessment system and collected data from several industrial internet platform enterprises. The purpose of the assessment is to find out the weaknesses of the existing IIPs, and grasp the development trend of the

IIPs. It is of great significance for promoting the continuous optimization of platforms and improving the development level of industrial Internet platform. In this section, we randomly select three platforms from the assessment system, and analyze the results to demonstrate the practical value of this study.

B. SYSTEM DEVELOPMENT

As shown in Figure 17, the authors developed an IIP assessment system and designed a set of questionnaires for IIP providers. Through the assessment, the construction level and development status of the IIP can be dynamically tracked, the development advantages of the platform can be clarified, and the weakness of the IIP can be deeply understood, so as to better guide the IIP providers to determine the development priorities and promote the development of the IIP.



FIGURE 17. Assessment System for Industrial Internet Platform.

As shown in Figure 18, the questionnaire of the assessment system includes both quantitative and qualitative collection items, with a ratio of 3:4.



FIGURE 18. Partial screenshot of the questionnaire for the assessment system.

TABLE 7. Indicator data collected by the industrial Internet platform assessment system.

Indicator Platform	A1	B1	B2	B3	A2	B4	B5	B6	B7	A3	B8	B9	Total Score
P1	34.2	66.9	42.9	20.4	21.7	37.7	20.5	23.2	12.8	22.9	27.3	14.1	24.4
P2	68.7	88.5	75.1	60.0	68.1	80.3	62.4	63.7	69.1	50.9	50.5	51.6	64.8
P3	49.6	77.1	51.0	40.0	38.0	59.5	46.9	48.7	12.2	58.7	59.2	57.9	44.5
Avg	50.8	77.5	56.3	40.1	42.6	59.2	43.3	45.2	31.4	44.2	45.7	41.2	44.6

A1(1st grade indicator): Foundation Guarantee;
 A3(1st grade indicator): Value and benefit
 B2(2nd grade indicator): Talent guarantee
 B4(2nd grade indicator): Cloud-based management and scheduling of resources
 B6(2nd grade indicator): Microservice deployment and invocation
 B8(2nd grade indicator): Platform application

A2(1st grade indicator): Key capability
 B1(2nd grade indicator): Strategic positioning
 B3(2nd grade indicator): Security system
 B5(2nd grade indicator): Management and mining of industrial big data
 B7(2nd grade indicator): Industrial APP development and application
 B9(2nd grade indicator): Open ecology

C. ANALYSIS OF ASSESSMENT RESULTS

According to the assessment method and process in Section IV-E, relevant data of IIPs is collected, analyzed and scored. The three randomly selected platforms can be denoted as P1, P2, P3. Specific scores of indicators is shown in Table 7. The average scores of foundation, key capability, value and benefit of the three platforms are 50.8, 42.6, and 44.2, respectively. It can be seen that these three platforms perform best in terms of “foundation”, perform generally in “value and benefit”, and perform worst in “key capabilities”. As shown in Figure 19, this result demonstrates that these platforms have good guarantee in foundation of “strategic positioning”, “talent guarantee” and “security system”. However, the key capabilities and the value and benefit of these platforms need to be further improved. From the perspective of foundation (see Figure 20), all these platforms generally have the lowest scores in the “security mechanism” and “security technology” (third grade indicator), which reveals the weakness in the security systems of these platforms.

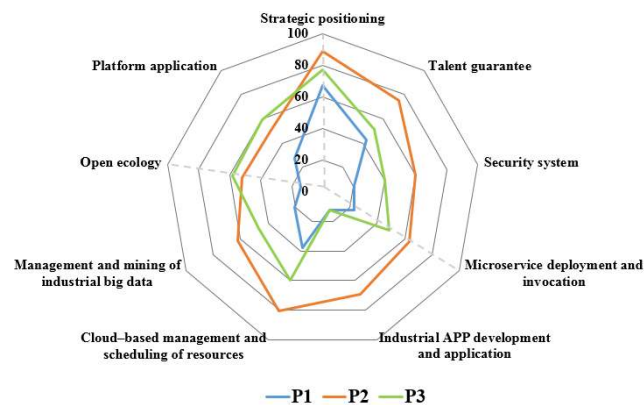


FIGURE 19. Radar map of the second-grade indicators.

From the perspective of key capability (see Figure 21), the platforms have poor performance in “data processing and analysis” (third grade indicator), so it is necessary to improve the functional status, data processing level and intelligent analysis capability.

From the perspective of value and benefit (see Figure 22), the performance of these platforms is relatively balanced and slightly worse in terms of “scale of application” (third

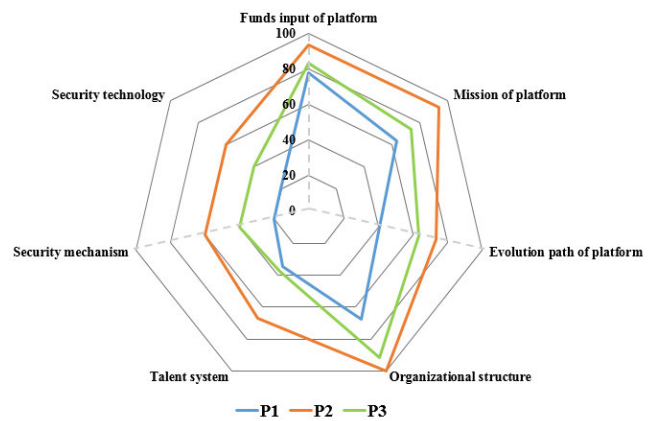


FIGURE 20. Radar map of foundation (third grade indicators).

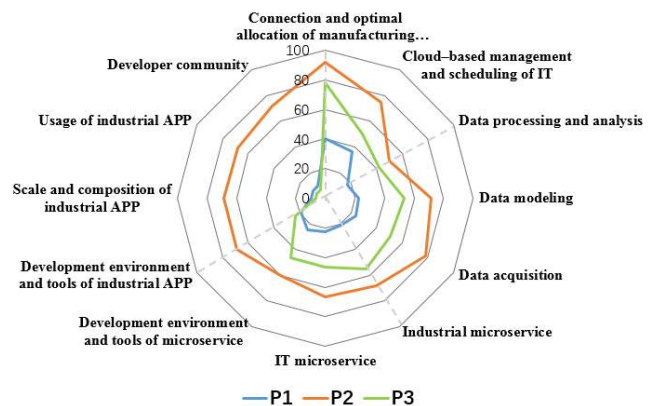


FIGURE 21. Radar map of key capacity (third grade indicators).

grade indicator). They should increase the user number, and optimize the user distribution and long-term served industry and scenarios.

From the perspective of each platform, the total score of P1 is 24.4 (see Table 7), which is the lowest among the three platforms. According to Figure 19, the shortcomings of P1 in terms of foundation, key capability, and value and benefit are “security system” (second grade indicator), “industrial APP development and application” (second grade indicator), and open ecology (second grade indicator), respectively.

The total score of P2 is 64.8 (see Table 7), which is the highest among the three platforms. P2 performs worst in terms of value and benefit. According to Figure 22,

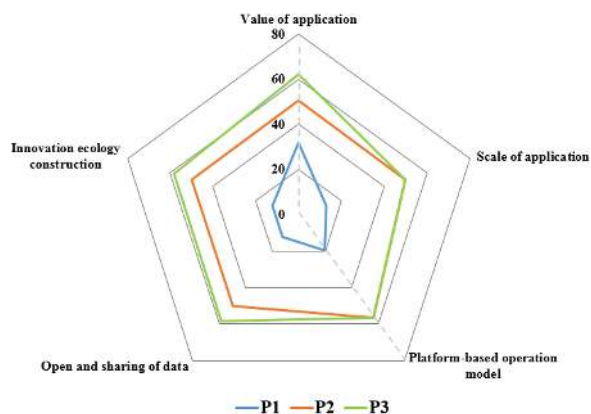


FIGURE 22. Radar map of value and benefit (third grade indicators).

the development level of “value of application” (third grade indicator), “open and sharing of data” (third grade indicator), “innovation ecology construction” (third grade indicator) should be improved parallelly.

The total score of P3 is 44.5 (see Table 7), ranking second among the three platforms. There are obvious shortcomings in terms of key capability. According to Figure 21, important breakthroughs can be made to improve the development level of key capability from two aspects: “usage of industrial APP” (third grade indicator), and “scale and composition of industrial APP” (third grade indicator).

VI. CONCLUSION

This study proposes a reference architecture and an assessment framework for IIP. On the one hand, this study provides the industry with a reference architecture for a unified understanding of IIP. On the other hand, it provides an effective approach for the industry to promote the development of IIP by means of assessment. Government departments can carry out the assessment in different industries, regions to find out the development status of IIP, clarify the key points and direction of guidance, and improve the policy effect. Platform providers can carry out self-evaluation and self-diagnosis continuously with the reference to the assessment system proposed in this study, so as to formulate relevant improvement strategies and measures.

The future works of this study mainly focuses on the three aspects.

1) In the future improvement of the assessment system, we will increase the assessment indicators for the comprehensive assessment of benefits from three aspects of society, economy and technology [57].

2) In the future work of IIP reference architecture, we plan to design industry-specific architectures by using computational intelligent aided design methods.

3) We plan to investigate more enterprises to verify the practical value of the assessment system. In addition, we expect to be able to adequately analyze the assessment results, formulate targeted diagnosis reports for the platform enterprises, and provide suggestions for their improvement.

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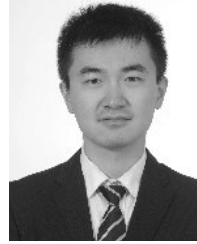
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