Cloud manufacturing architecture: a critical analysis of its development, characteristics and future agenda to support its adoption

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Abstract

Purpose – In the last decade, cloud manufacturing (CMfg) has attracted considerable attention from academia and industry worldwide. It is widely accepted that the design and analysis of cloud manufacturing architecture (CMfg-A) are the basis for developing and applying CMfg systems. However, in existing studies, analysis of the status, development process and internal characteristics of CMfg-A is lacking, hindering an understanding of the research hotspots and development trends of CMfg-A, and effective guidance is lacking on the construction of superior CMfg-As. The purpose of this paper is to review the relevant research on CMfg-A via identification of the main layers, elements, relationships, structure and functions of CMfg-A to provide valuable information to scholars and practitioners for further research on key CMfg-A technologies and the construction of CMfg systems with superior performance.

Design/methodology/approach – This study systematically reviews the relevant research on CMfg-A across transformation process to internal characteristics by integrating quantitative and qualitative methods. First, the split and reorganization method is used to recognize the main layers of CMfg-A. Then, the transformation process of six main layers is analysed through retrospective analysis, and the similarities and differences in CMfg-A are obtained. Subsequently, based on systematic theory, the elements, relationships, structure and functions of CMfg-A are inductively studied. A 3D printing architecture design case is conducted to discuss the weakness of the previous architecture and demonstrate how to improve it. Finally, the primary current trends and future opportunities are presented.

Findings – By analyzing the transformation process of CMfg-A, this study finds that CMfg-A resources are developing from tangible resources into intangible resources and intelligent resources. CMfg-A technology is developing from traditional cloud computing-based technology towards advanced manufacturing technology, and CMfg-A application scope is gradually expanding from traditional manufacturing industry to emerging manufacturing industry. In addition, by analyzing the elements, relationships, structure and functions of CMfg-A, this study finds that CMfg-A is undergoing a new generation of transformation, with trends of integrated development, intelligent development, innovative development and green development. Case study shows that the analysis of the development trend and internal characteristics of the architecture facilitates the design of a more effective architecture.

Research limitations/implications – This paper predominantly focuses on journal articles and some key conference papers published in English and Chinese. The reason for considering Chinese articles is that CMfg was proposed by the Chinese and a lot of Chinese CMfg-A articles have been published in recent years. CMfg is suitable for the development of China's manufacturing industry because of China's intelligent manufacturing environment. It is believed that this research has reached a reliable comprehensiveness that can help scholars and practitioners establish new research directions and evaluate their work in CMfg-A.

Originality/value – Prior studies ignore the identification and analysis of development process and internal characteristics for the current development of CMfg-A, including the main layers identification of different CMfg-As and the transformation process analysis of these main layers, and in-depth analysis of the inner essence of CMfg-A (such as its elements, relationships, structure and functions). This study addresses these limitations and provides a comprehensive literature review.

Keywords: cloud manufacturing; architecture; main layers; future directions

Paper type: Review paper

1 Introduction

Cloud manufacturing (CMfg) is a product of the deep cross-integration between advanced manufacturing modes (such as the manufacturing grid, agile manufacturing, and networked manufacturing) and the new generation of information technologies (such as cloud computing, the Internet of Things (IoT), and virtualization). It is an emerging manufacturing mode that has attracted considerable attention from academia and industry worldwide since it was first proposed (Li et al., 2010). Many scholars have studied the definition, architecture, key technologies and applications of CMfg. Among them, scholars have consistently focused on the research and design of CMfg-A because they are the architectural blueprint for building CMfg service platforms and are also related to the development of an entire CMfg system.

The design of different CMfg-As shows scholars' perceptions and expectations regarding CMfg. By analysing CMfg-A, it is possible to have a clear understanding of the development process, ideas and future of CMfg. Therefore, in the past decade, many scholars have studied CMfg-A, with most scholars focusing on the design of CMfg-A with different structures and functions. Only a few scholars have commented on the design ideas and characteristics of CMfg-A; Table I summarizes the content and methods of their studies. Although scholars have summarized current CMfg-A research from different perspectives, these studies still have several major limitations: 1) Descriptive analysis of existing CMfg-As, such as the distribution of dates of publication, research institutions, researchers and journals, is lacking. 2) The literature on CMfg-A is increasing year by year; however, because analysis of the development process of CMfg-A is lacking, it is difficult to understand the popular research directions and development trend of CMfg-A. 3) Existing studies simply analyse the external characteristics of CMfg-A (such as its operation process, construction method and layer information), and in-depth analysis of the inner essence of CMfg-A (such as its elements, relationships, structure and functions) is lacking, thus hindering an understanding of the development laws and key technologies of CMfg-A.

Table I. Review papers on cloud manufacturing architecture (CMfg-A)

Contents	**Methods**	**References**
Operation process of CMfg-A	Multi-view description: (function view, resource view, information view and process view)	Lv (2012)
Construction method of CMfg-A	Method classification: (modular method and multi-level method)	Wu and Xu (2014)
Hierarchical information of CMfg-A	Summary in the form of a table	Qi et al. (2015) Zhu et al. (2015)
Characteristics of CMfg-A	Comparative analysis: (comparing cloud computing architecture and CMfg-A)	Liu et al. (2019a)

By collecting studies on CMfg-A, this work systematically identifies and understands CMfg-A through an analysis of the relevant articles identified, hoping to effectively guide future research on CMfg-A and to further promote the application and implementation of CMfg. The contributions of this study are as follows:

1) Six main layers are found by splitting and reorganizing the hierarchy of CMfg-A. Then, by analysing the development process of and the similarities and differences in these layers, the popular research directions of each layer and the development trend of CMfg-A are revealed.

2) From the perspective of elements, relationships, structure and functions, the internal characteristics of CMfg-A are inductively analysed, providing meaningful guidance for an in-depth understanding of the internal operation process of CMfg-A and for further research on the construction of superior CMfg systems.

3) Based on the analysis of the main layers, elements, relationships, structure, functions and characteristics of architecture, the previous 3D printing architecture is improved, providing meaningful guidance for further architecture design.

The rest of this study is organized as follows: First, Section 2 introduces the research questions and the methods of the literature collection. Second, Section 3 finds the main layers of CMfg-A and analyses the development process of and the similarities and differences in these main layers. Third, the elements, relationships, structure, functions and characteristics of CMfg-A are inductively studied and a 3D printing architecture design case is conducted in Section 4. Subsequently, Section 5 discusses the future development opportunities for CMfg-A based on the analysis in Sections 3 and 4. Finally, conclusions are drawn in the last section.

2 Research design

2.1 Research questions

To analyse in depth the inherent characteristics and development laws of CMfg-A and to effectively guide future research on CMfg-A, this study proposes the following research questions based on the limitations mentioned in Section 1 and further addresses these research questions in the remaining parts.

RQ1: What are the development history of and the similarities and differences in CMfg-A? The answer to this question is given in Section 3.

RQ2: What are the internal characteristics and development laws of CMfg-A from the perspective of elements, relationships, structure and functions? The answer to this question is given in Section 4.

RQ3: What are the future research directions of CMfg-A? The answer to this question is given in Section 5.

2.2 Research methodology and boundaries

To make this literature review more comprehensive, objective and effective, this study first selected peer-reviewed English-language journal papers published in the Scopus database. And then, considering that CMfg was originally proposed by Chinese scholars and most of the literature related to CMfg is also Chinese literature, this study also selected peer-reviewed Chinese-language journal papers published in the China National Knowledge Infrastructure (CNKI) database. This study assumes that such selection can obtain the broadest cognition and effectively identify the key features in the research and development (R&D) of CMfg-A. The literature selected in this paper started in 2010 (when CMfg was proposed) and ended in May 2020. A total of 66 articles were carefully chosen after considering the inclusion and exclusion criteria. The detailed article search process is presented in Table II.

Step 1: Keyword search. This study used “cloud manufacturing” and “architecture” as the query string. At the same time, to further expand the relevant research content, other query strings related to CMfg-A were identified after discussion with other authors, including “manufacturing cloud”, “cloud computing”, “hierarchy” and “hierarchical structure”. All articles with these query strings in the title, keywords or abstracts were selected. A total of 572 works, including journal articles, conference papers, patents, books and chapters, were found.

Step 2: Screening of valuable literature. Since journal papers and Institute of Electrical and Electronics Engineers (IEEE) conference papers are generally considered to have high cognitive value, this study selected 272 articles that were journal papers or IEEE conference papers for review.

Step 3: Refining, selecting and sorting. By carefully reading the full text of the downloaded articles (Step 2), those that solely consider “cloud manufacturing” or “architecture” rather than focusing on “cloud manufacturing architecture” were removed. Governmental documents, regulations, laws, CMfg practical projects, corporate activities, webpages, handbooks, and reports were not considered in this study. Finally, 66 papers were selected as the literature objects in this study.

Table II. Steps involved in the selection of articles

Steps	Details
Step 1: Keyword search	- Query string: “cloud manufacturing” OR “manufacturing cloud” OR “cloud computing” AND “architecture” OR “hierarchy” OR “hierarchical structure”. - Search databases: Scopus and CNKI. - Search space: article title OR abstract OR keywords. - Article type: peer-reviewed journal papers. - Time range: published from January 1, 2010 to May 31, 2020.
Step 2: Screening of valuable literature	- To guarantee a similar quality level for the papers, articles published in journals or IEEE conference proceedings in the Scopus and CNKI databases were considered.
Step 3: Refining, selecting and sorting	- The authors carefully read the full texts of the downloaded articles (Step 2) and defined clear boundaries to delimit the search to ensure that the articles truly focus on the CMfg-A field.

3 Discussion of the main layers

Due to space limitations, the descriptive analysis of the 66 papers is presented in Appendix A. It shows the research status of CMfg-A from the perspective of dates of publication, researchers, research institutions and the journal distribution. With the development of CMfg, many scholars use the multi-layer construction method to establish CMfg-A with different layers. Therefore, an effective analysis addresses the development laws and trends of CMfg-A from different layers. In this section, the main layers of CMfg-A are found through decomposing and classifying the hierarchy of the 66 papers; then, the development process of these main layers is analysed to identify the popular research directions of and similarities and differences in CMfg-A.

3.1 Identification of the main layers

In this study, the hierarchical structure of the 66 selected papers is split, and a total of 357 layers are obtained. Then, by classifying the layers with the same function, the layer allocation table shown in Table III is obtained.

As shown in Table III, the application layer, resource layer, core service layer, resource virtualization layer and application interface layer rank among the top five, together accounting for more than 54% of the total. Notably, the first CMfg-A given by Chinese scholars Li et al. (2010) includes the following five layers: (1) the physical resource layer, (2) CMfg virtual resource layer, (3) CMfg core service layer, (4) application interface layer, and (5) CMfg application layer. These five layers are completely consistent with the five layers in Table III, which is sufficient to demonstrate their importance. The architecture proposed by Li et al. (2010) also includes an auxiliary “cloud security layer”, which is gradually expanded to form the basic supporting layer. The basic supporting layer ranks sixth in Table III, indicating its importance.

In addition, many of the remaining layers in Table III are derived from these six layers. For example, the business layer adds enterprise factors based on the application layer; the resource awareness layer is part of the resource virtualization layer; and the cloud security layer, network layer, standard and specification layer and platform-integrated operating environment are all sub-parts of the basic supporting layer. Therefore, this study regards the application layer, resource layer, core service layer, resource virtualization layer, application interface layer and basic supporting layer as the main layers of CMfg-A. They basically contain the process and technologies of CMfg implementation, and CMfg-As with different layers and functions subsequently proposed have evolved and expanded based on these six main layers.

Table III. Layer distribution of cloud manufacturing architecture

Layer name (other names)	Frequency	Proportion
Application layer (terminal application layer, user layer, enterprise cooperation application layer, presentation layer, application integration layer, application management layer, application mode layer, application service operation centre)	52	14.6%
Resource layer (physical resource layer, resource/capability layer, manufacturing resource layer, knowledge resource layer, manufacturing capability layer, manufacturing resources and capabilities)	50	14.0%
Core service layer (manufacturing cloud core service layer, core function layer, core cloud service layer, global service layer, service layer, cloud service operation layer, service discovery layer)	38	10.6%
Resource virtualization layer (virtualized resource library, virtual resource layer, virtual service layer, virtualization layer, virtual packaging layer, cloudization layer, virtualization and awareness layer)	35	9.8%
Application interface layer (interface layer, user interaction interface, user interface layer, interactive layer, portal layer, CMfg service interactive portal)	21	5.9%
Basic supporting layer (supporting layer, infrastructure layer, platform supporting layer, infrastructure service layer, IoT/cloud platform system (CPS) infrastructure)	16	4.5%
Business layer (business model layer, business process layer, business intelligence layer)	13	3.4%
Resource awareness layer (perception layer)	12	2.8%
Middleware layer (platform service middleware)	10	2.8%
Management layer (knowledge organization management, knowledge and data management, resource management layer, service management layer)	10	2.0%
Network layer (transmission network layer, wider network layer)	7	1.7%
Cloud security layer (security assurance system)	6	1.7%
Service operation layer (service optimization scheduling layer, service supply and demand matching layer)	6	1.4%
Platform-integrated operating environment	5	1.4%
Tool layer (cloud service platform tool layer, toolkit layer)	5	1.4%
Service component layer (platform service component layer)	5	1.4%
Data layer (data collection layer, basic data layer)	5	1.4%
Service construction layer (platform service construction layer, platform service layer, service building platform)	5	1.1%
Standard specification layer	4	1.1%
Knowledge layer (knowledge base layer)	4	1.1%
Technical layer (technical system layer)	4	0.8%
Service integration layer (service bus layer, enterprise service bus layer, system integration enabler)	3	0.6%
Platform layer (CMfg service platform)	2	0.6%
Transaction layer	2	0.6%
Service monitoring layer	2	0.6%
Cloud service model layer	2	0.6%
Engine layer	2	8.7%
Others	31	3.4%
Total	357	100%

3.2 Development process of the main layers

In Section 3.1, six main layers of CMfg-A are obtained. In the following, this study analyses the development process of these main layers of the 66 papers included in this review to determine the popular research directions of and the similarities and differences in CMfg-A.

(1) The resource layer

The function of the resource layer is to provide the CMfg platform with the various resources involved in the full life cycle of products through resource providers. The biggest difference between resource layers is the description and classification of resources. Therefore, the classification of 50 resource layers in Section 3.1 is presented in Table IV. It can be seen from the table that manufacturing resources and manufacturing capacity, R service resources and S service resources, hard resources and soft resources often appear in pairs.

Table IV. Classification of resource layers

Resource Type	Frequency	Year of appearance
physical resources	6	2010-2014
R service resources	3	2010,2011,2013
S service resources	3	2010,2011,2013
manufacturing resources	22	2010-2019
manufacturing capability	16	2010-2019
Hard resources	5	2011,2013-2015
Soft resources	4	2011,2013,2015
Knowledge resources	3	2012,2015,2017
Intelligent manufacturing products	3	2017-2019

The initial resource layer includes only physical resources (Li et al., 2010), such as manufacturing equipment, servers, PCs, and machining centres. However, these physical resources represent only a small part of all CMfg resources, which are constantly expanded and improved with the development of different architectures. To facilitate management and application, scholars have performed studies on resources. For example, from the perspective of small and medium-sized enterprises, the CMfg resources in the resource layer are divided into two categories: R service resources with simple interaction and S service resources with complex cooperative contract relationships (Huang et al., 2013, Yin et al., 2011). To facilitate the configuration and use of cloud resources, the resource layer is divided into two parts: manufacturing resources and manufacturing capabilities (Tao et al., 2011b, Zhang et al., 2010), this classification method has been recognized by most scholars (Adamson et al., 2017) and has been widely used in recent years. In addition to manufacturing resources and manufacturing capabilities, intelligent manufacturing products were added to the resource layer in 2019 based on the interpretation of the "intelligence +" era (Li et al., 2019). The transformation of the resource layer is shown in Figure I.

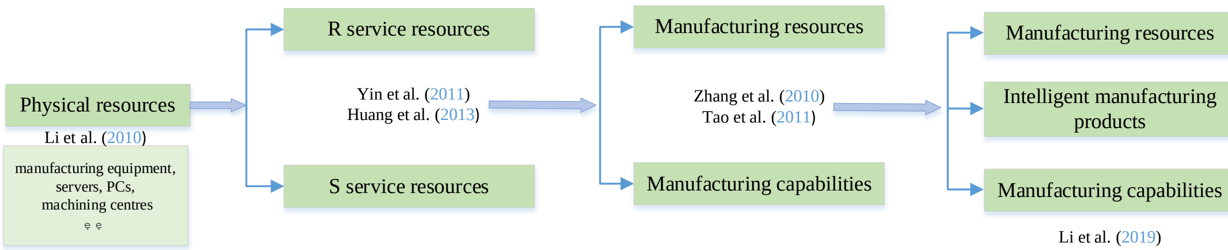

Figure I. The transformation of the resource layer

The development process of the resource layer mainly depends on the classification of resources and the specific types of resources. Therefore, to analyse the development process of the resource layer, this study compares and integrates the cloud resources included in the architectures of the 66 papers included in this review and records the date when each type of resource first appeared. Figure II is the classification structure tree of cloud resources. It can be seen from Figure II that cloud resources have the following development process:

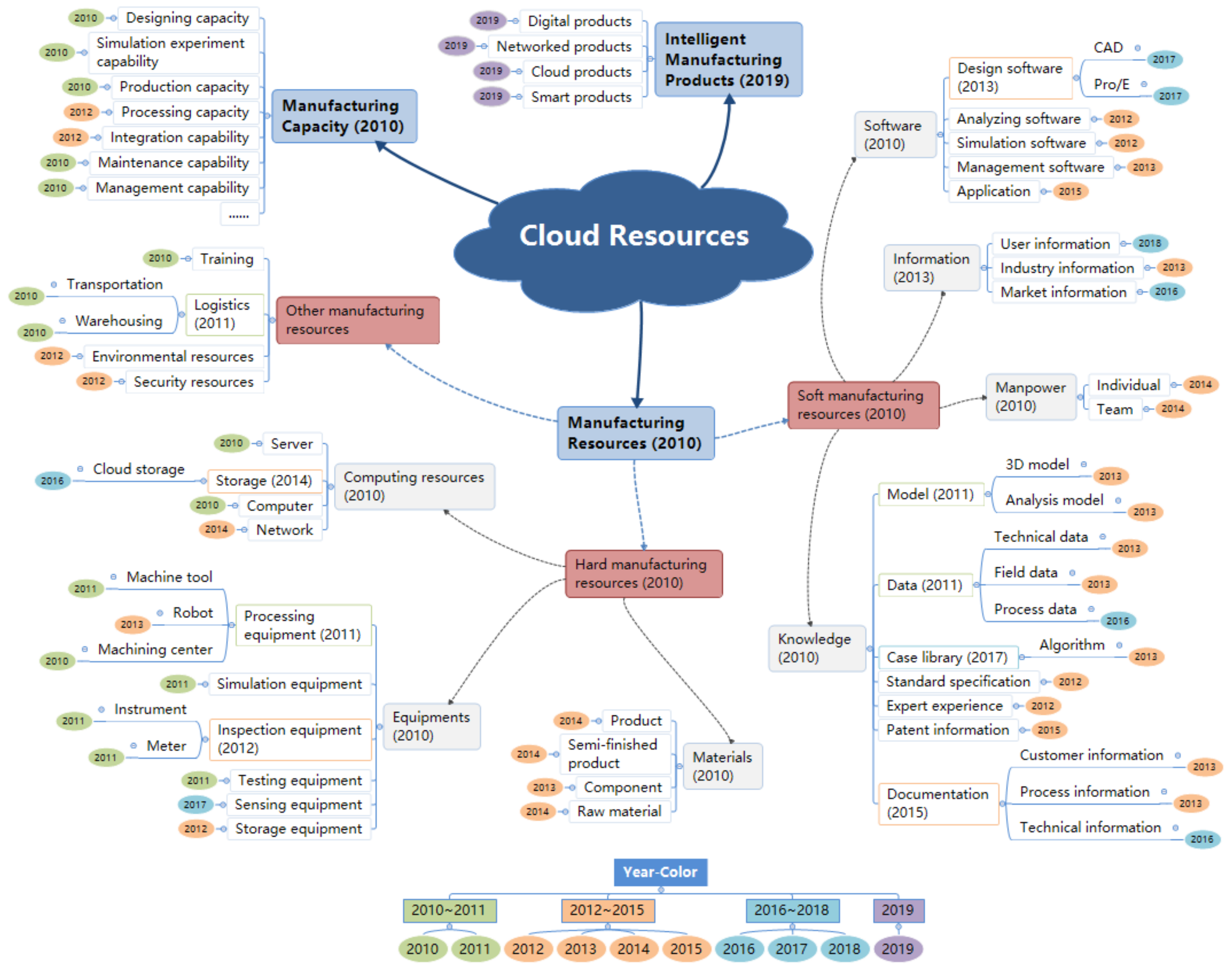

Figure II. The classification structure tree of cloud manufacturing resources

1) The transformation of cloud resources from diversification to intelligence: Regarding the date when various resources emerged, the general structure of cloud resources (classification of manufacturing resources and manufacturing capabilities) was initially formed from 2010 to 2011, and some subdivided manufacturing resources and manufacturing capabilities have appeared, but mainly focused on hard resources and manufacturing capabilities. From 2012 to 2015, with the deepening of research on CMfg-A, the number of types of cloud resources have grown very rapidly, especially the soft manufacturing resources, forming a clear classification of software, information, manpower, and knowledge. However, there were fewer newly added cloud resources from 2016 to 2018, and the increase is mainly the outermost periphery of the tree diagram, that is, a more detailed division of resources. For example, design software is divided into computer-aided design (CAD) and Pro/E software commonly used in the manufacturing industry. In 2019, the category

of manufacturing products was added, which reflects the demand for intelligent manufacturing. Therefore, the analysis finds that the development of cloud resources has experienced a process from diversified development to stable development, and is currently in a change period with intelligent manufacturing products as the breakthrough point.

2) The transformation of cloud resources from physical resources to abstract resources: In terms of the content of cloud resources, compared with manufacturing capabilities and intelligent manufacturing products, the classification of manufacturing resources is more detailed, and the tree diagram extends further. Manufacturing resources are subdivided into hard resources, soft resources and other related resources according to their forms of existence and use. Hard resources include all kinds of manufacturing equipment, computing resources and materials that are indispensable to the traditional manufacturing industry. Soft resources include software, knowledge, information and manpower. Among them, knowledge, an intellectual resource, has been highly valued since CMfg was first proposed. By constructing knowledge service system architectures (Li et al., 2012c), personalized knowledge service architectures (Li et al., 2015) and new product development knowledge management systems (Yin et al., 2017) under the CMfg environment, scholars have studied key technologies such as knowledge resource modelling and semantic query. With the deepening of people's cognition, manufacturing ability – the capability combined with manufacturing resource elements in manufacturing activities – has gradually become the core part of cloud resources. It is an invisible, dynamic form of a special resource that must be studied separately. By studying the multi-dimensional information model of manufacturing capacity, scholars have proposed the manufacturing capacity description system framework in the CMfg mode (Luo et al., 2012), and studied modelling and description methods for multi-dimensional information related to manufacturing capacity (Luo et al., 2013). The meta-model of manufacturing capability service description, the manufacturing capability service management method and the manufacturing capability service assessment method have also been proposed to deepen the comprehensive understanding of and research on manufacturing capability (Lin et al., 2016). Therefore, the analysis finds that there are more research results on manufacturing resources because recognition and generalization are easy due to their physical existence. Abstract resources such as knowledge, intellectual resources and manufacturing capabilities have gradually become the research focus of scholars.

To sum up, the analysis of the development process of the resource layer shows that although there are slight differences in the resource classification of the CMfg resource layer, cloud resources can be roughly classified into three categories: manufacturing resources, manufacturing capability and intelligent manufacturing products. From 2010 to 2019, cloud resources have undergone two transitions: from diversification to intelligence, and from tangible resources into intangible resources. The research on abstract resources and intelligent manufacturing products will be the future trend. There is little research on intelligent manufacturing products because they have only recently been proposed. However, the addition of represents the gradual integration of artificial intelligence technology into the development of CMfg, which is believed to be able to develop quickly in the "intelligence +" era.

(2) The resource virtualization layer

The function of the resource virtualization layer is to aggregate various resources connected to the network into virtual resources and to encapsulate virtual resources into cloud services through service definition tools, virtualization tools and other tools and then publish them to the CMfg service centre. The development process of the resource virtualization layer mainly depends on the functions and technologies of resource virtualization. Therefore, to analyse the development process of the resource virtualization layer, this study compares and integrates the functions and technologies of resource virtualization in 47 resource virtualization layers (include 12 resource perception layers) in Section 3.1 and records the date when each type of function and technology first appeared (as shown in Table V).

Table V. Functions and technologies of resource virtualization layer

Functions		**Technologies (Equipment)**	**Year**
Resource Perception	Identification	RFID	2010
		EPC	2010
		Barcode	2010
		Radar	2019
	Sensor	GPS	2010
		PC	2010
		Infrared sensor	2013
		Laser scanning	2013
		Webcam	2014
		Remote sensing	2019
Resource Connection	Access	Interface adapter	2010
		Sensor adapter	2010
		Network adapter	2014

		Storage adapter	2014
		Software adapter	2014
		Knowledge-class adapter	2014
		Technology class adapter	2014
		Model adapter	2014
		IoT	2012
		Embedded cloud computing	2013
		Distributed technology	2018
Resource Communication	The Internet	Mobile internet(2G/3G/4G)	2011
		Satellite communication network	2011
		WIFI	2011
		ZIGBEE	2017
		Ethernet	2019
	Security	Block chain	2018
	Data processing	Monitor	2013
		Data screening	2015
		Big data	2018
		Edge Computing	2019
Resource Virtualization	Description	Ontology（OWL）	2012
		UML Modeling	2013
		EXPRESS	2013
		XML Description	2013
		Semantic Web	2017
	Registration	--	--
	Publish	--	--
Service Encapsulation	Service Classification	--	--
	Service Mapping	E Topology Mapping	2012

It can be seen from Table V that the functions of resource virtualization layer include five parts: resource perception, connection, communication, virtualization and service encapsulation. The research on resource virtualization started from the research on resource perception and interconnection functions in 2010, including identification devices, sensing devices and adapters(Li et al., 2010, Zhang et al., 2010). In 2011, the transmission network in the communication function was added (Ren et al., 2011). In 2012, IoT technology was applied to the resource connection function (Tao et al., 2014a, Tao et al., 2014b), and the description function of resource virtualization and the mapping function of service encapsulation were proposed. In 2013, data monitoring and processing functions were proposed. From 2014 to 2016, technologies and equipment added more abundantly on the basis of the previous. Since 2017, in addition to improving the original functions, some interdisciplinary technologies have gradually appeared to better realize the functions of the resource virtualization layer, such as semantic network, big data, blockchain technology, distributed technology and edge computing. In addition, to emphasize the process of digitizing and virtualizing physical resources, the “cloud” digitalization function has been transformed into a resource perception system, refining the ways and approaches of perception, connection, communication of resources in CMfg (Zhang et al., 2010). The remaining functions are included in the virtual resource pool layer. Subsequently, many studies have generally adopted the form of the resource perception layer and virtual resource layer (Li and Yin, 2016, Tao et al., 2014a, Tao et al., 2011b, Adamson et al., 2017, Ren et al., 2015). The resource perception layer realizes the perception and access of resources, while the resource virtualization layer realizes the virtualization, encapsulation, registration and publication of resources. The transformation of the resource virtualization layer is shown in Figure III.

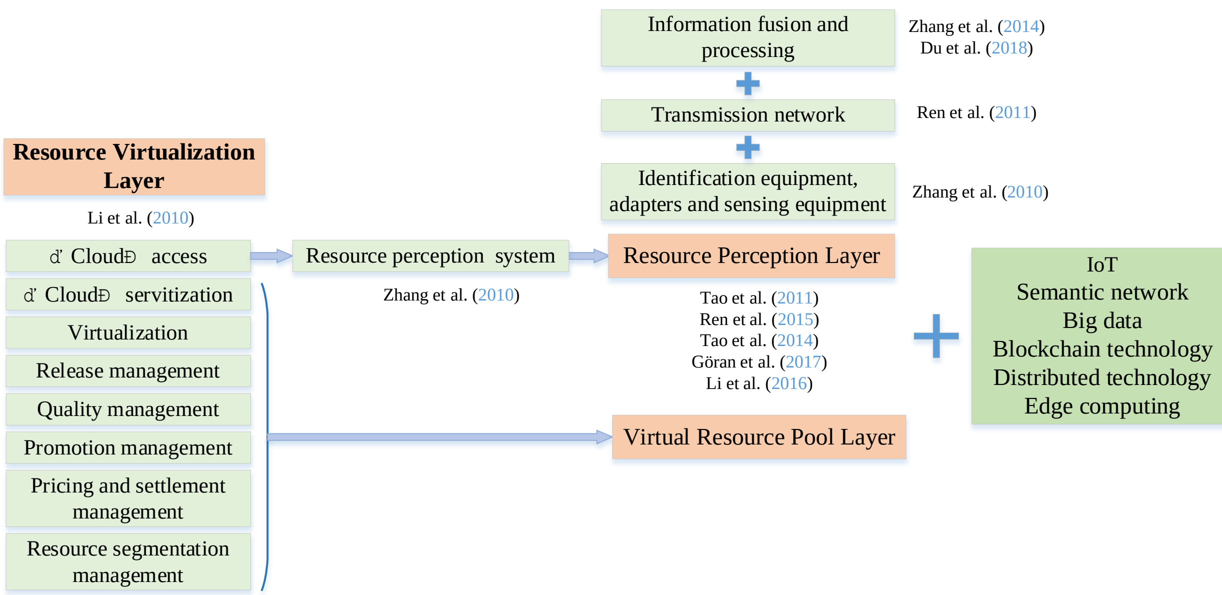

Figure III. The transformation of the resource virtualization layer

To sum up, the analysis of the development process of the resource virtualization layer shows that the current design of this layer is mainly focused on the function of resource perception, connection, communication, virtualization; however, there are few researches on service encapsulation, quality management, promotion management, pricing and settlement management, and resource segmentation management. They are all important technologies for realizing this layer and warrant further study. Besides, the design of the resource virtualization layer has a tendency to move towards cross-discipline, such as big data, blockchain, edge technologies and so on.

(3) The core service layer

The function of the core service layer is to comprehensively manage CMfg systems and to optimize the configuration of cloud services to provide users with flexible and dynamic cloud services. The core services layer mainly includes various management of requirements, tasks, services and users. Therefore, this study compares and integrates the management functions of the core service layer contained in 66 architectures (Figure IV) and classifies them by year to analyze the development process of the core service layer.

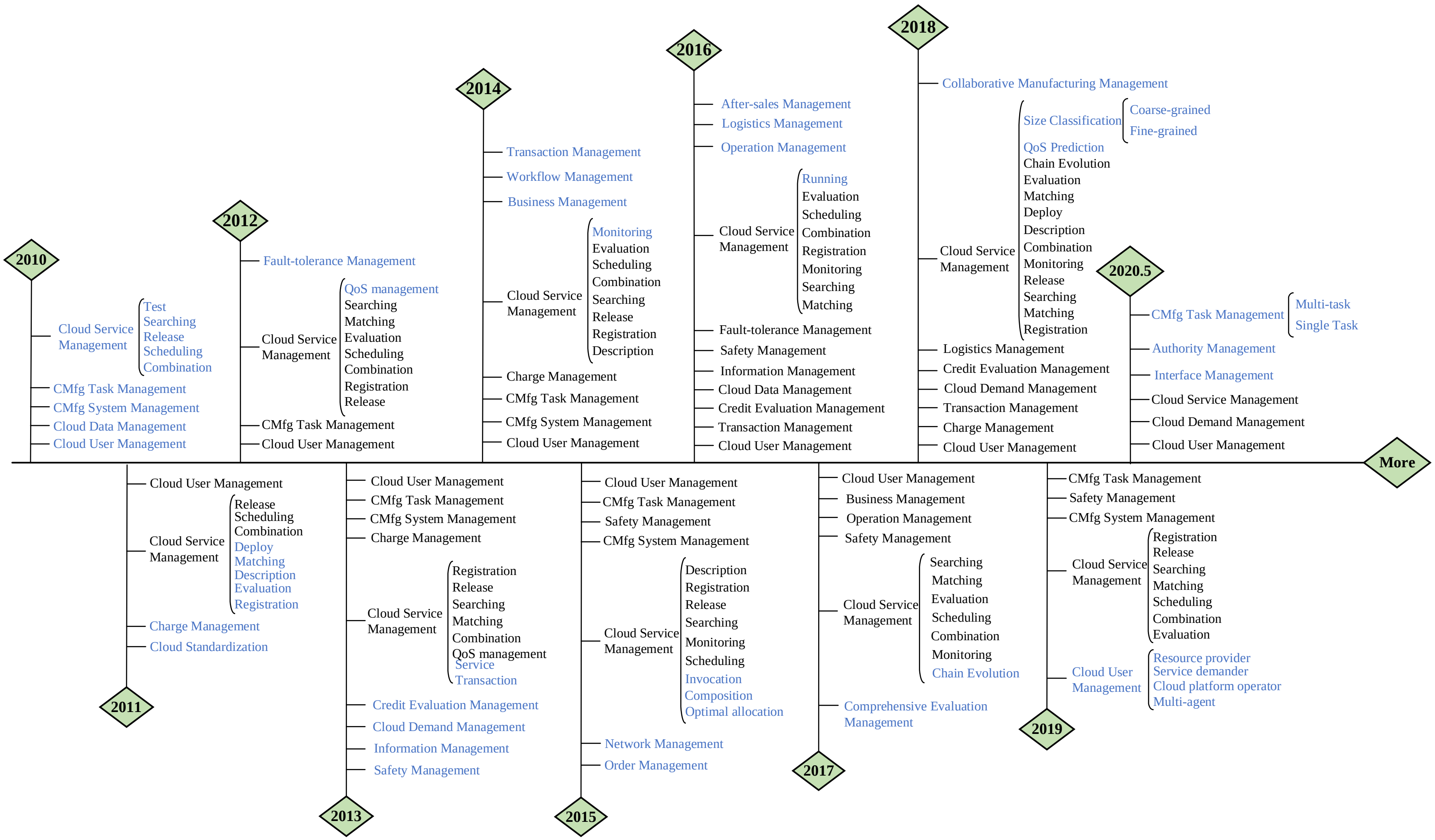

Figure IV. The management functions of the core service layer

As shown in Figure IV， the main functional framework of the core service layer was formed in 2010, including cloud user management, CMfg system management, cloud data management, CMfg task management and cloud service management. With the deepening of the research, the management functions of the core service layer are gradually increased. For example, cloud standardization, charge management and other cloud service management were added in 2011, fault-tolerant management was added in 2012, and credit evaluation management, cloud demand management, information management and security management were added in 2013. It is noteworthy that each year after 2014 has emphasized the importance of CMfg transactions and business, including order management, transaction management, business management and collaborative manufacturing management, indicating that the core service layer pays more attention to the real order-related functions and gradually moving toward achieving the implementation of CMfg. In addition, the function of cloud user management has appeared from 2010 to 2020, indicating that the interests of users are very important to CMfg. In 2019, user management was classified, emphasizing multi-subject user management. Meanwhile, to facilitate better management of cloud services, some scholars have adjusted the form of services. For example, service processing is divided into cloud service models, meta-models and meta-meta-models that facilitate the description and release of cloud services (Huang et al., 2012). Services are divided into service components with different levels of granularity that invoke services faster and more efficiently (Yin et al., 2011). CMfg services are divided into three categories: public cloud services, hybrid cloud services and private cloud services. Different types of services are composed and invoked in different ways, making them easier to manage and apply (Tang et al., 2012). In 2018, service management was classified (coarse-grained and single-grained services), emphasizing multi-grained service management. In 2020, task management was classified (single task and multi-task), emphasizing multi-task management. Therefore, it is proven that the core service layer of CMfg is gradually developing towards multi-agent, multi-task, and multi-granularity services.

To sum up, the analysis of the development process of the core service layer shows that the current design of this layer is mainly focused on the management of cloud services, especially the optimal composition and scheduling of cloud services (Chen et al., 2016). Related combination methods, solving algorithms and quality-of-service (QoS) evaluation have been the research hotspots in recent years. Management research on CMfg transaction, such as order management, transaction management, business management and collaborative manufacturing management, is gradually increasing (Ren et al., 2015, Wang et al., 2019). In addition, the core service layer has a trend toward the management of multi-agent, multi-task and multi-granularity services, which require further research.

(4) The application interface layer

The function of the application interface layer is to provide different professional application interfaces and general management interfaces such as user registration and authentication for specific manufacturing application fields. The transformation of the resource virtualization layer is shown in Figure V. The initial application interface layer includes different professional application interfaces, such as distributed simulation tools, online order management tools, model publishing tools, and general interfaces (Li et al., 2010). Subsequently, some scholars have expanded online order management tools, emphasizing the importance of CMfg transactions and business. For example, the business model layer defines business processes for customers' business needs and then calls different service components to meet different business needs (Yin et al., 2013, Huang et al., 2013, Yin et al., 2011). The business process layer binds services into a process through matching and orchestration, and it supports users in defining business processes according to business needs (Li and Yin, 2016, Li et al., 2012c, Yao et al., 2012). The transaction layer is designed to support service matching, service transaction, credit evaluation and other aspects of CMfg business (Huang et al., 2013). In addition, some scholars have emphasized the importance of tools and proposed the tool layer, which supports various professional application interfaces (Li et al., 2012d, Ren et al., 2015, Huang et al., 2013).

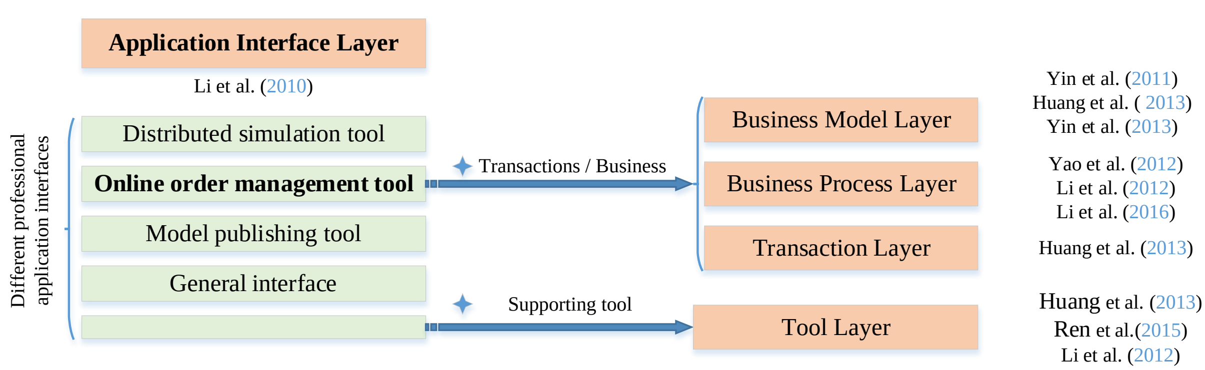

Figure V. The transformation of the application interface layer

To sum up, the analysis of the development process of the application interface layer shows that due to the fragmented functions of this layer and because the purpose of both the application layer and application interface layer is to support services in the CMfg application field, some scholars omit the application interface layer or combine this layer and the application layer into one layer when designing the architecture. In addition, the original professional application interfaces in the application interface layer have evolved into the user-oriented tool layer and related layers for business services.

(5) The application layer

The function of the application layer is to provide on-demand services to users in various fields and industries. The transformation of the resource virtualization layer is shown in Figure VI. The initial application layer conceived some business requirements, including new product development, complex problem solving, large-scale simulation, and complex product virtual prototyping, as well as user interfaces, terminals and interfaces (Li et al., 2010). Subsequently, to cater to various service applications throughout the product life cycle, business needs were expanded, including analysis, design, simulation, manufacturing, management, maintenance and others (Tao et al., 2014b, Zhang et al., 2010). Li et al. (2010) believe that CMfg can also realize functions such as supporting a single agent to complete a certain stage of manufacturing and supporting multi-agent collaboration to complete a certain stage of manufacturing, to complete multi-stage manufacturing and to obtain manufacturing capabilities on demand (Tao et al., 2011a). With the deepening of CMfg-A research, the scope of the application layer has also gradually expanded, from traditional manufacturing industries (such as the waste resource remanufacturing industry (Tang et al., 2012), mould industry (Li et al., 2012a, Gu et al., 2012), computer numerically controlled (CNC) processing industry (Liu et al., 2012), logistics industry (Wang et al., 2012a), aerospace industry (Wu et al., 2012), steel industry (Xiong et al., 2012), auto and motorcycle parts industry (Yin et al., 2013), CNC tool industry (Liu and Zhou, 2013), electronic component industry (Zhou and Yuan, 2013) and forging industry (Wang et al., 2016)) to emerging manufacturing industries (the water-saving equipment industry (Lv and Li, 2016), elevator industry (Xiao et al., 2018), 3D printing industry (Li and Zhang, 2018) and robotics industry (Adamson et al., 2015)).

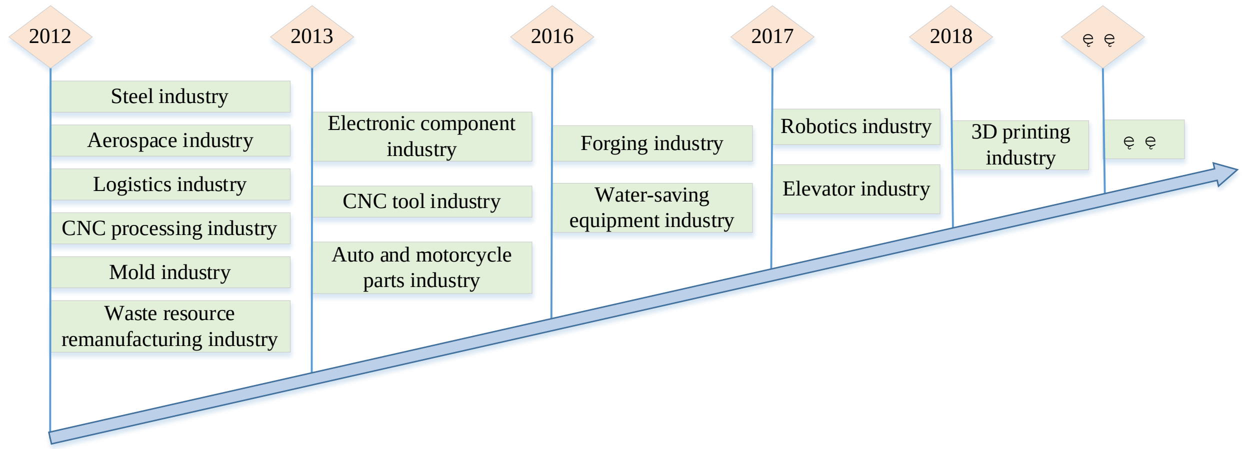

Figure VI. Changes in the application industry

As the communication bridge between CMfg users and CMfg platforms, user interfaces and terminals have become the research focus in recent years. In addition to entering the portal through a web browser (Tao et al., 2011a, Yin et al., 2013), users can enter the portal using a personal digital assistant (PDA), tablet computer, mobile phone and other mobile terminals (Xiong et al., 2012). Moreover, to emphasize that users can access and use cloud services through various human-computer interaction interfaces, scholars have constructed the portal layer (Tao et al., 2011b) and proposed a research framework of pervasive human-computer interaction technology in the CMfg environment to analyse key human-computer interaction technologies (Ma et al., 2011).

To sum up, the analysis of the development process of the application layer shows that with the continuous development of information technology, the scope of application of CMfg has gradually expanded, from the initial specific application field to the product full life cycle application field and from the traditional manufacturing industry to emerging manufacturing industries, fully demonstrating that the application maturity of CMfg has gradually increased with the deepening of CMfg research. However, there are still few application achievements in emerging industries. In this regard, it is still necessary to understand the needs of specific industries and enterprises and then explore step-by-step, feasible CMfg implementation solutions.

(6) The basic supporting layer

The function of the basic supporting layer is to provide basic support during the entire operation of CMfg. The basic supporting layer mainly includes various foundation supports.

Therefore, this study compares and integrates the foundation supports contained in 66 architectures (Table VI) to analyze the development process of the basic supporting layer.

Table VI. Foundation supports of the foundation support layer

Foundation Supports	Year
Cloud Security (Access control, Encrypted transmission, Secure storage)	2010-2020 (2011)
Cloud Network (Internet, Intranet, Extranet)	2010-2016 (2011)
Knowledge	2011-2015
Quality of Service (QoS)	2011, 2013
Cloud Monitoring	2011, 2013, 2018
Cloud Storage	2011-2013, 2016, 2018
Cloud Server	2011-2013, 2015, 2016, 2018
Cloud Database	2011-2013, 2015, 2016, 2018
Cloud Communication	2012, 2015
Standards and Specifications	2012, 2013, 2018, 2019
Cloud Memory	2013
Cloud Computing	2013, 2016
Integrated Operating Environment (Policy environment, Financial environment, Demand environment, Alliance environment)	2013, 2018 (2018)
Internet of Things (IoT)	2016
Information Manufacturing Technology	2016
Cloud Protocol	2018
Blockchain Technology	2018

As shown in Table VI, in 2010, the basic supporting layer only includes cloud security that provides security protection functions and cloud network that provides interconnection functions (Zhang et al., 2010). Cloud security and cloud network are the most important and indispensable of all supports, especially cloud security, which has been mentioned from 2010 to 2020. In 2011, cloud security was expanded, including access control, encrypted transmission, and secure storage; cloud network was expanded, including Internet, Intranet and Extranet; knowledge, quality of service (QoS), cloud monitoring, cloud Storage, cloud Server, cloud database, cloud communication and other support components were proposed (Tao et al., 2011b, Yin et al., 2013, Yin et al., 2011). In 2012, cloud communication, standards and specifications were proposed (Li et al., 2012c). In 2013, cloud memory, cloud computing and integrated operating environment were proposed (Huang et al., 2013, Zhang and Qi, 2013). In 2016, Internet of Things (IoT) and information manufacturing technology were proposed. In 2018, cloud protocol and blockchain technology were proposed. The integrated operating environment was classified, including policy environment, financial environment, demand environment and alliance environment.

To sum up, the analysis of the development process of the basic supporting layer shows that with the deepening of people's understanding, the content of the supporting layer has become increasingly rich, starting with the initial cloud security and finally forming a comprehensive integrated supporting layer that includes cloud security, the transmission network, cloud knowledge, standard specification and the platform-integrated operating environment.

3.3 Similarities and differences in the main layers

Analysing the development process of the six main layers, this study finds that the similarities and differences in CMfg-A are as follows:

The similarities in CMfg-A are reflected in two aspects: 1) Unified main layers are the first. Although different scholars have proposed CMfg-A with different layers and functions, the six main layers (the application layer, resource layer, core service layer, resource virtualization layer, application interface layer and basic supporting layer) remain unchanged. 2) Consistent design concepts are the second. The design of architecture takes the resource layer as the input, the application layer as the output, and the cloud platform as the centre for the centralized management and operation of cloud resources, cloud services and cloud tasks to successfully complete transactions.

The differences in CMfg-A are reflected in three aspects: 1) Different emphases are the first. Different CMfg-As emphasize different structures and functions. For example, some architectures emphasize the awareness (Tao et al., 2014b), virtualization (Ren et al., 2011), discovery and searching (Wang et al., 2012b) of resources; other architectures emphasize the management (Hu et al., 2012) and modelling (Bai et al., 2017) of services; and still other architectures emphasize human-computer interaction (Ma et al., 2011). 2) Different description perspectives of architectures are the second. From different perspectives, scholars build architecture with different levels and functions. At present, CMfg-A construction includes the resource integration perspective (Li et al., 2012b), business process perspective (Yin et al., 2013, Zhang et al., 2020), service perspective (Huang et al., 2013) and network perspective (Sluga et al., 2017). 3) Different application objects are the third. Under different application requirements, scholars have designed CMfg-As for different application objects, for example, architectures for small and medium-sized enterprises, for large conglomerates and for industrial alliances. Through application demonstration, existing architectures are further improved and perfected by summarizing experience and determining problems, finally ensuring the realization of the application effect.

4 Discussion of elements, relationships, structure and functions

IEEE standard 610-R defines “architecture” as “the structure of the components, their relationships, and the principles and guidelines that govern their design and evolution over time”. It can be seen that an architecture contains components, relationships, structure and guidelines. A CMfg-A is a system composed of elements that are interrelated, and the system structure determines the function of the system. Therefore, elements, relationships, structure and functions are regarded as necessary parts of CMfg-A.

Using multi-view method to describe architecture is essential for a comprehensive and in-depth analysis of the characteristics of CMfg-A (Lv, 2012). Therefore, this study inductively analyses and describes the elements, relationships, structure and functions of CMfg-A, providing a basis for understanding in depth the inherent characteristics of CMfg-A and comprehensively understanding the current status of CMfg-A.

4.1 Elements

Section 3.1 determines the main layers of CMfg-A: the resource layer, resource virtualization layer, core service layer, application interface layer, application layer and basic supporting layer. Analysing the development process of these six main layers in Section 3.2, this review finds that the application interface layer has gradually been integrated into the application layer with the deepening of research. Therefore, this study regards the resource layer, resource virtualization layer, core service layer, application layer and basic supporting layer as the core layers of CMfg-A. The following analyses the basic elements of the overall CMfg-A by analysing the elements of each layer in the architecture.

1) The resource layer provides various types of CMfg resources involved in the manufacturing life cycle. The elements involved in this layer are cloud resource providers and cloud resources (manufacturing resources, manufacturing capabilities and intelligent manufacturing products). 2) The resource virtualization layer virtualizes and encapsulates various resources connected to the network into cloud services. The elements involved in this layer are cloud resources, virtualization tools and cloud services. 3) The core service layer carries out comprehensive management of the CMfg platform and performs tasks such as cloud service searching, matching and combination. The elements involved in this layer include cloud platforms, cloud services, various management tools and cloud platform operators that support the entire transaction operation of CMfg. 4) The application layer provides the portal website and man-

machine interface for CMfg users to access a cloud manufacturing system. The elements involved in this layer include cloud tasks, cloud service users and portal interfaces. 5) The basic supporting layer provides a comprehensive integrated supporting environment including cloud security, the transmission network, cloud knowledge, standard specification and the platform-integrated operating environment. The elements involved in this layer include various types of supporting parts. The corresponding relationships between the five core layers and the basic elements of CMfg-A are shown in Figure VII.

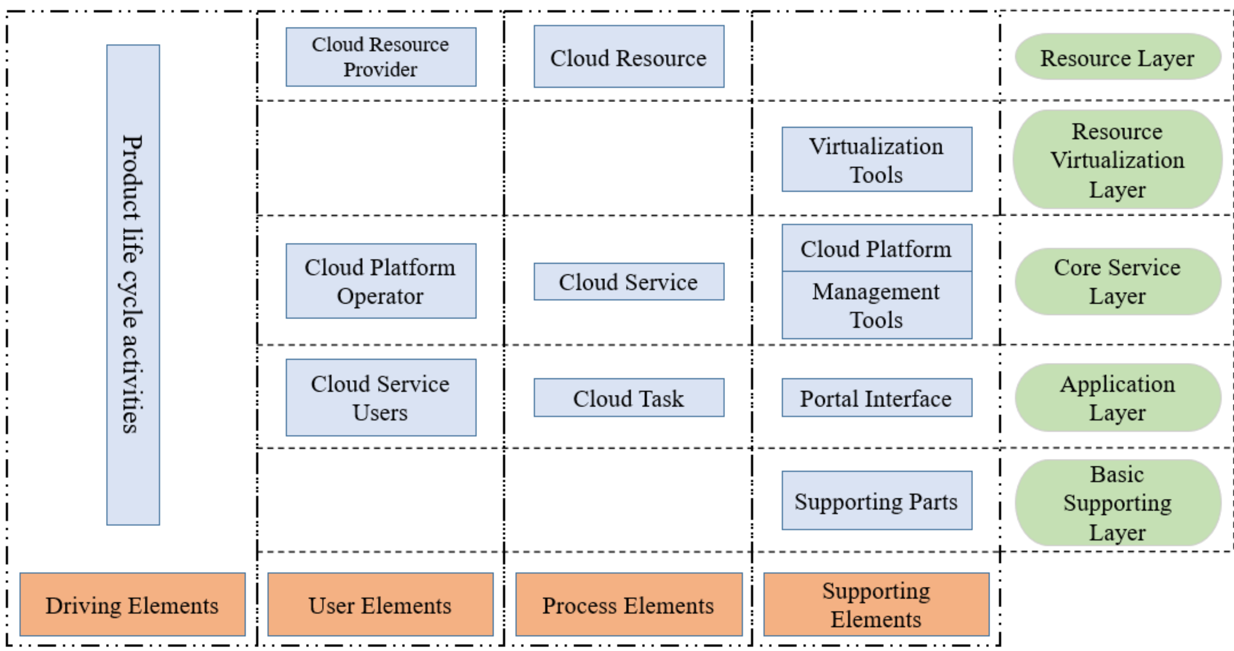

Figure VII. Basic elements of cloud manufacturing architecture

The basic elements of the overall CMfg-A are obtained based on the analysis of the above five core layers, which can be summarized into four parts: 1) driving elements: the full life cycle activities of CMfg products; 2) user elements: cloud resource providers, cloud platform operators and cloud service users; 3) process elements: cloud resources (manufacturing resources, manufacturing capabilities, intelligent manufacturing products), cloud services and cloud tasks; and 4) supporting elements: cloud platforms, virtualization tools, management tools, portal interfaces, and supporting parts that support the entire transaction operation of CMfg.

4.2 Relationships

Once the basic elements of CMfg-A are obtained, analysing the relationships between the CMfg system and each element is key to revealing the internal laws of CMfg-A and the foundation for studying the structure and functions of CMfg-A.

The basic elements of CMfg-A include driving elements, user elements, process elements and supporting elements. Driving elements are the core elements that drive the operation of the system. The activities of the full life cycle of products are fundamental to promoting the operation of CMfg systems, including analysis, design, simulation, manufacturing, management, maintenance, after-sales service, recycling and other activities. User elements are the human factors involved in CMfg systems. Cloud resource providers provide the resources required by CMfg systems; cloud platform operators operate the cloud platform and provide various cloud services; and cloud service users publish application requirements. Process elements are the dynamic products involved in the entire CMfg transaction process, including cloud resources, cloud services, and cloud tasks. Supporting elements provide various supporting parts for manufacturing full life cycle activities.

Manufacturing life cycle activities (driving elements) run through the entire CMfg system and are related to all other elements. With the support of various supporting parts and digital, networked, cloud-based and intelligent tools (supporting elements), cloud resource providers (user elements) provide manufacturing resources, manufacturing capabilities and intelligent manufacturing products (process elements) in the whole life cycle of products. Cloud resources are provided to the cloud platform (supporting elements) in the form of cloud services (process elements) after virtualization and servitization. Cloud platform operators (user elements) manage and operate cloud services efficiently and match cloud tasks (process elements) and cloud services according to the application requests of cloud service users (user elements) in a dynamic manner. With the support of the cloud platform, cloud service users (user elements) use various cloud services on demand and realize multi-agent collaborative interaction. In this process, people, technology/equipment, management, data, materials, and capital (six elements) as well as the people flow, technology flow, management flow, data flow, logistics flow, and capital flow (six flows) of all life cycle activities are integrated to complete all kinds of activities in the whole life cycle of manufacturing with high quality and high efficiency to improve the market competitiveness of enterprises (or groups). The internal relationships of CMfg-A are shown in Figure VIII.

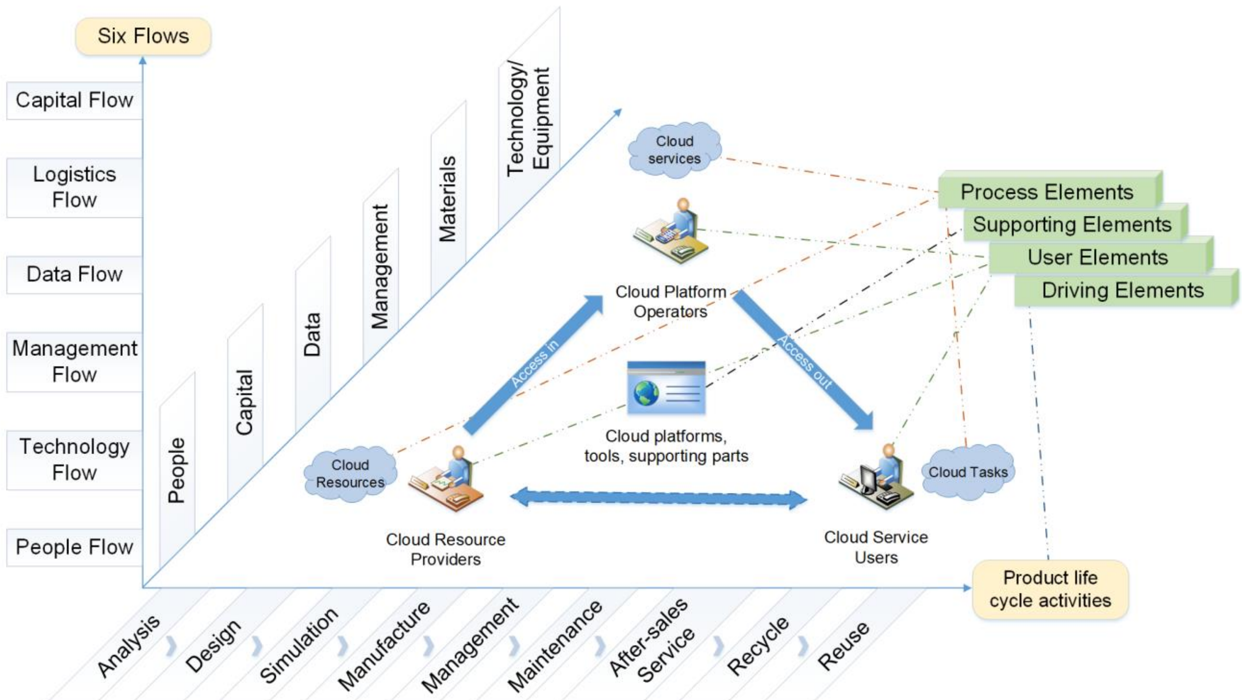

Figure VIII. Internal relationships of cloud manufacturing architecture

4.3 Structure

After analysing the basic elements of each layer of CMfg-A in Section 4.1 and the relationships between these basic elements and the CMfg operation process in Section 4.2, this study analyses the structure of CMfg-A (as shown in Figure IX) by combining the five core layers, basic elements and CMfg operation mode of CMfg-A.

The left side of Figure IX shows the five core layers of CMfg-A, with the resource layer as the input, the application layer as the output and the basic supporting layer as the global support. Advanced technologies and related operations are used to complete the transformation and matching of cloud resources, cloud services and cloud tasks quickly and accurately. The right side of Figure IX is the system operation mode, which integrates the basic elements of CMfg-A. The core layers and operation mode are connected by various tools and supporting parts.

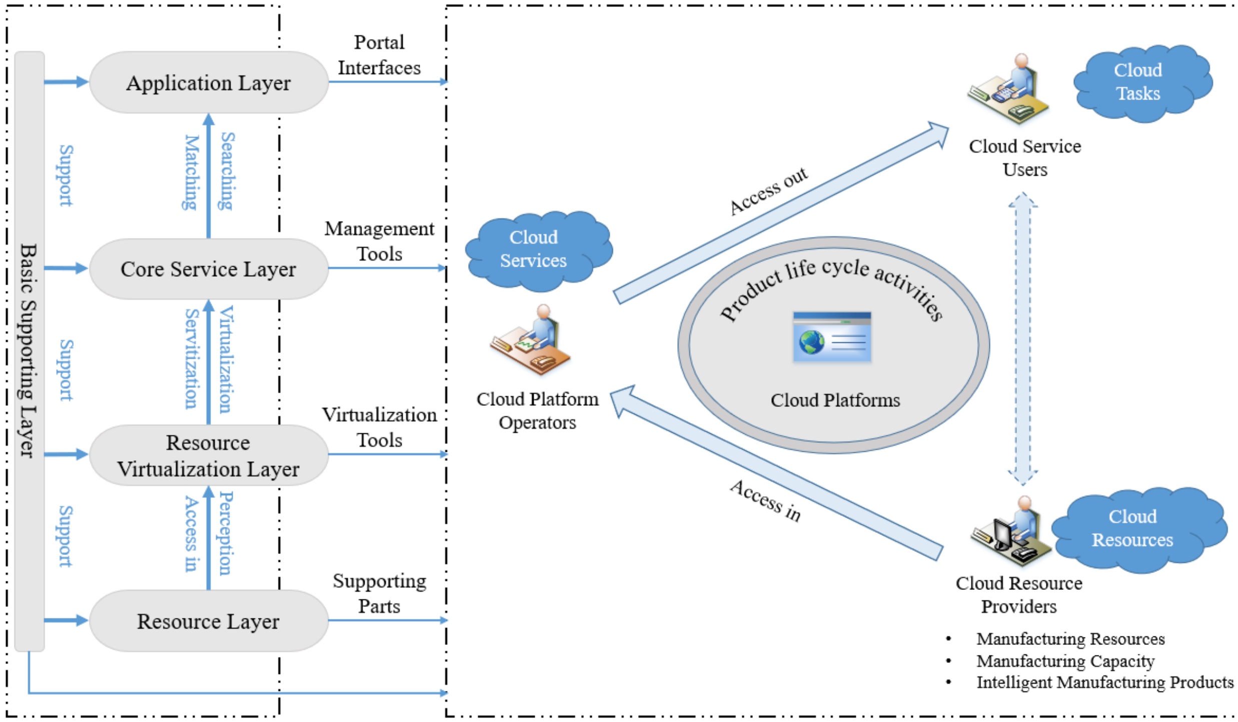

Figure IX. Structure of cloud manufacturing architecture

The analysis of the structure of CMfg-A finds that although the architectures proposed by scholars are not the same, they share a common idea: Around a product's full life cycle activities, three types of users (cloud resource providers, cloud platform operators and cloud service users) operate cloud resources, cloud services and cloud tasks. How to use advanced technologies, related tools and supporting parts to complete product business processes quickly and accurately is the core of CMfg systems.

4.4 Functions

Any architecture is a unity of functions. CMfg-A design is used to implement different basic functions and application functions. Basic functions refer to the functions performed within CMfg-A, while application functions refer to the functions reflected in different application modes.

Combined with the basic elements of the architecture, this study divides the basic functions of CMfg-A into user management functions, resource management functions, task management functions and security management functions. Among them, user management functions include user registration, login, edit and elimination; resource management functions include resource perception, access, description, encapsulation, registration, release, search and service combination; task management functions include task description, decomposition, schedule, reorganization, matching and status monitoring; and security management functions include certification, authentication, data compression, information encryption, real-time service monitoring and security policies. Figure X is the tree diagram of the basic functions of CMfg-A.

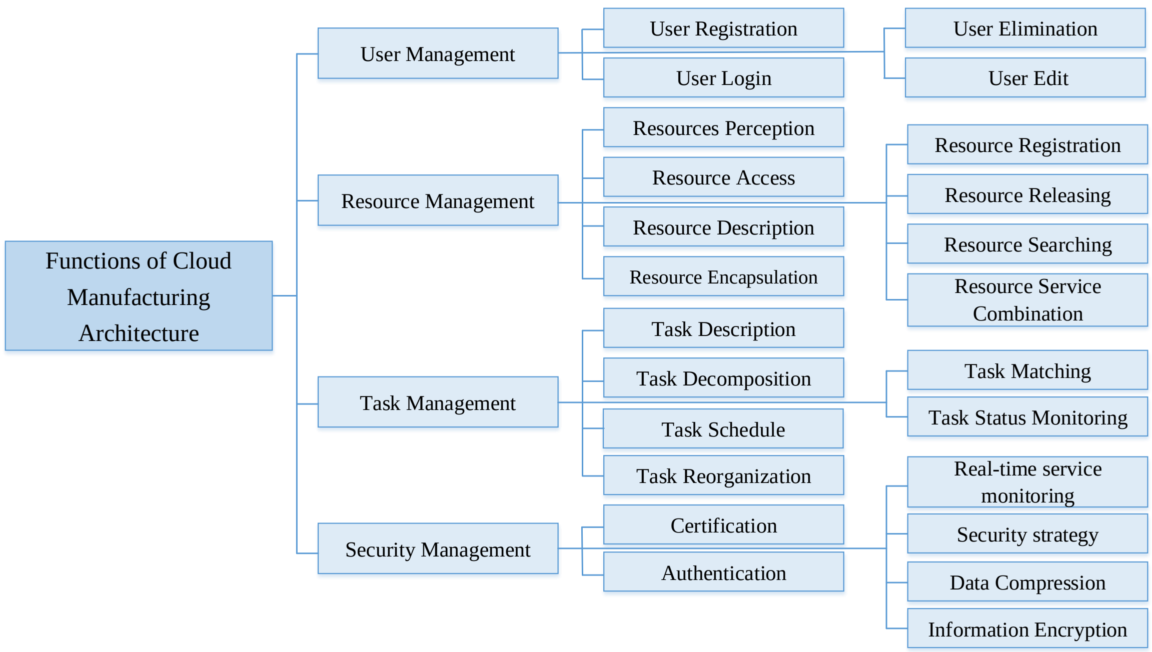

Figure X. The basic functional tree of cloud manufacturing architecture

According to different application modes, this study divides the application functions of CMfg-A into three categories: functions for "public clouds", functions for "private clouds" and functions for "regional clouds". The object of "public cloud" functions is the public service CMfg platform for the majority of small and medium-sized enterprises. These types of functions generally include unified user management, manufacturing service matching systems, manufacturing service transaction management, manufacturing service business management, business credit evaluation and analysis, industry knowledge gathering and service networked communities, service platform system management and other functions (Yin et al., 2011). The object of the "private cloud" function is the CMfg service platform within large group enterprises. These types of functions generally include cloud enterprise dynamic construction, product manufacturing process management, order processing, production plan formulation, production plan execution, settlement and other functions (Zhan et al., 2011). The object of the "regional cloud" function is the comprehensive CMfg service platform of the regional manufacturing industry. These types of functions generally include independent R&D, product life cycle management, production and manufacturing, integration of offline software and online services, industrial chain formation and other functions (Sheng et al., 2012). Table VII shows the application functions of CMfg-A.

Table VII. Application functions of cloud manufacturing architecture

Type of Application Function	Objects	Functions
"Public Clouds"	Small and medium-sized enterprises	Unified user management, manufacturing service matching system, manufacturing service transaction management, manufacturing service business management, business credit evaluation and analysis, industry knowledge gathering and service networked community, service platform system management, etc.
"Private Clouds"	Large group enterprises	Cloud enterprise dynamic construction, product manufacturing process management, order processing, production plan formulation, production plan execution and settlement, etc.
"Regional Clouds"	Regional manufacturing industry	Independent R&D, product life cycle management, production and manufacturing, integration of offline software and online services, industrial chain formation, etc.

4.4 Characteristics of cloud manufacturing architecture

Through analysis of the elements, relationships, structure and functions of CMfg-A and comparison with the architecture of other related manufacturing modes, such as networked manufacturing (Fan et al., 2005), applications service providers (ASPs) (Yang et al., 2004), the manufacturing grid (Fan et al., 2004) and agile manufacturing (Wang et al., 2005), this study finds that CMfg-A design is characterized by the gradual improvement of specific functions at different layers according to different application requirements. Then, based on existing technologies and tools and the integration of disciplines and emerging technologies, continuous innovation is conducted to design more intelligent and efficient CMfg-As. Specifically, CMfg-A has the following four characteristics:

(1) Demand traction, gradually improving functions

Different CMfg service models require different CMfg-As. Based on the core layer of the current CMfg-A, scholars take into account the problems faced by the current manufacturing development process and fully consider the characteristics and application requirements of manufacturing enterprises to improve the structure of the original architecture and gradually improve the specific functions of each layer (Adamson et al., 2019).

(2) Interdisciplinary and technological integration

With the gradual increase in demand for CMfg applications, the existing manufacturing informatization theory and technology foundation have difficulty achieving all the functions of CMfg-A. Therefore, through the intersection with other related disciplines (such as manufacturing execution systems (Li and Yin, 2016), industrial alliances (Xiao et al., 2018), and blockchain (Du et al., 2019, Dong et al., 2019)) and the integration of emerging technologies (such as cloud computing, IoT, big data, virtualization, web services, the semantic web, and edge computing), the functions of CMfg-A are realized, and the various key technologies required are conquered.

(3) Continuous innovation to adapt to intelligent development

With the development of a new generation of artificial intelligence technology, advanced manufacturing technology is deeply integrated with a new generation of such technology as well as new information and communication technology, and the manufacturing industry has entered a new "intelligent +" era (Li et al., 2019). Under the guidance of the new generation of artificial intelligence technology, CMfg-A adapts to new changes through theoretical innovation, model innovation, functional innovation and technological innovation.

(4) Development towards emerging industries

With the deepening of research, the application fields of CMfg-A have gradually expanded, with such fields extending from traditional manufacturing industries, such as the gear industry, forging industry and mould industry, to emerging manufacturing industries, such as the robotics industry and 3D printing industry. At the same time, the maturity of applications in various manufacturing fields has also gradually increased.

4.5 An improvement case of 3D printing architecture

The design of a good architecture is closely related to the main layers, elements, relationships, structure, and functions of the architecture. Therefore, this study takes 3D printing as an example, analyses the weaknesses of the previous 3D printing cloud platform architecture and improves it based on the analysis of the main layers, elements, relationships, structure, functions and characteristics in Sections 3 and Sections 4.

Figure XI shows the most commonly used 3D printing cloud platform architecture in recent studies proposed by Guo and Qiu (Guo and Qiu, 2018). The architecture includes 4 layers (manufacturing resources and their access, virtual resource pool, service layer and interaction layer), and each layer is divided into several components. The architecture has the following obvious weaknesses:

1) Incomplete functions and technologies. The 3D printing cloud platform architecture lacks many key functions and technologies. For example, the manufacturing resources and access layer lacks perception and access functions of 3D printing resources; The virtual resource pool layer lacks virtualization and servitization technologies; The service layer lacks cloud user, demand, transaction, pricing and logistics management and other management functions that are critical to the manufacturing of 3D printing CMfg products. In addition, the 3D printing cloud platform architecture lacks application layer and basic supporting layer, that is, it lacks the application and the necessary supporting technologies of the cloud platform. Different functions and technologies are essential parts of the realization of CMfg-A, and the absence of any part cannot completely realize the manufacturing of 3D printing in CMfg.

2) Lack of clear classification. The architecture does not effectively classify the components in each layer. For example, in the resource layer, software resources and computing resources belong to manufacturing resources, 3D printer belong to equipment resources in manufacturing resources, and ability resources belong to manufacturing capabilities. The lack of clear resource classification will not only affect the effective implementation of subsequent virtualization and servitization technologies of resources, but also hinder the searching, matching and management functions of 3D printed resources. In the service layer, service monitoring, service publication and service selection are service management functions, while task generation and task allocation are task management functions. The lack of clear function classification will complicate the manufacturing process and make management more time-consuming.

3) Incorrect locations of functions. Some functions and layers in the architecture do not match. For example, “management resources” in the resource layer is not the resources of 3D printing, it belongs to the function of the service layer; “user data” and “task data” in the virtual resource pool layer, “service selection” and “evaluation” in the interface layer are belong to the functions of the service layer. The wrong locations of functions mislead the real role of these layers.

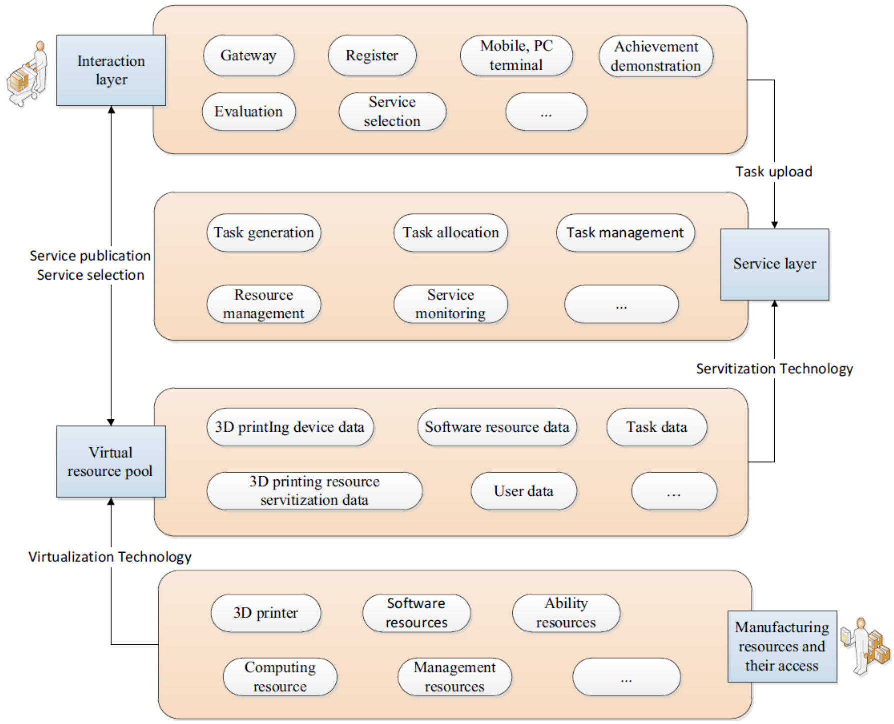

Figure XI. The most commonly used 3D printing cloud platform architecture in recent studies

To solve the above weaknesses, this study improves the architecture based on the analysis of the main layers, elements, relationships, structure and functions in Sections 3 and Sections 4. The specific improvements are as follows:

1) Improve the architecture based on the development analysis of 6 main layers. a) In the resource layer, the 3D printing resources are classified into manufacturing resources (include material, equipment, software, manpower, knowledge resources and other manufacturing resources), manufacturing capabilities (include design, simulation, processing, test, integration capability and other capabilities) and 3D printing intelligent manufacturing products. In addition, the importance of intelligent resources and abstract resources is emphasized based on the analysis in Section 3.2. b) The resource virtualization layer is divided into two parts. The first part includes the technologies and equipment of perception, access, communication, information fusion and processing, virtualization and servitization function. The second part are virtual resource pools, including manufacturing resource pool, manufacturing capacity pool and intelligent manufacturing product pool, corresponding to classification of resources. c) The core service layer considers the comprehensive management of users, demand, task, evaluation, logistics, transaction and charge,

and classifies cloud service management in detail. d) The user interface layer complements the ubiquitous terminal interaction devices and emphasizes the portal interface for three types of users. e) The new architecture adds an application layer and a basic supporting layer. The application layer classifies 3D printing manufacturing modes and emphasizes the requirements of users. The basic supporting layer lists the basic supporting parts required by the 3D printing cloud platform in detail.

2) Improve the architecture based on the analysis of elements, relationships, structure, and functions. a) Based on the analysis of elements in Section 4.1. First, add user elements to the architecture. Then, for process elements, cloud resources are embodied in the resource layer, cloud services are embodied in the core service layer, cloud tasks are embodied in the application layer. The supporting elements are embodied in the basic supporting layer. b) Based on the analysis of relationships in Section 4.2, incorporate 3D printing manufacturing full life cycle activities into the architecture, with elements and flows throughout the CMfg system. c) Based on the analysis of structure in Section 4.3, adjust and add the relationship between the layers of the architecture. d) Based on the analysis of function in Section 4.4, integrate various management functions into the core service layer.

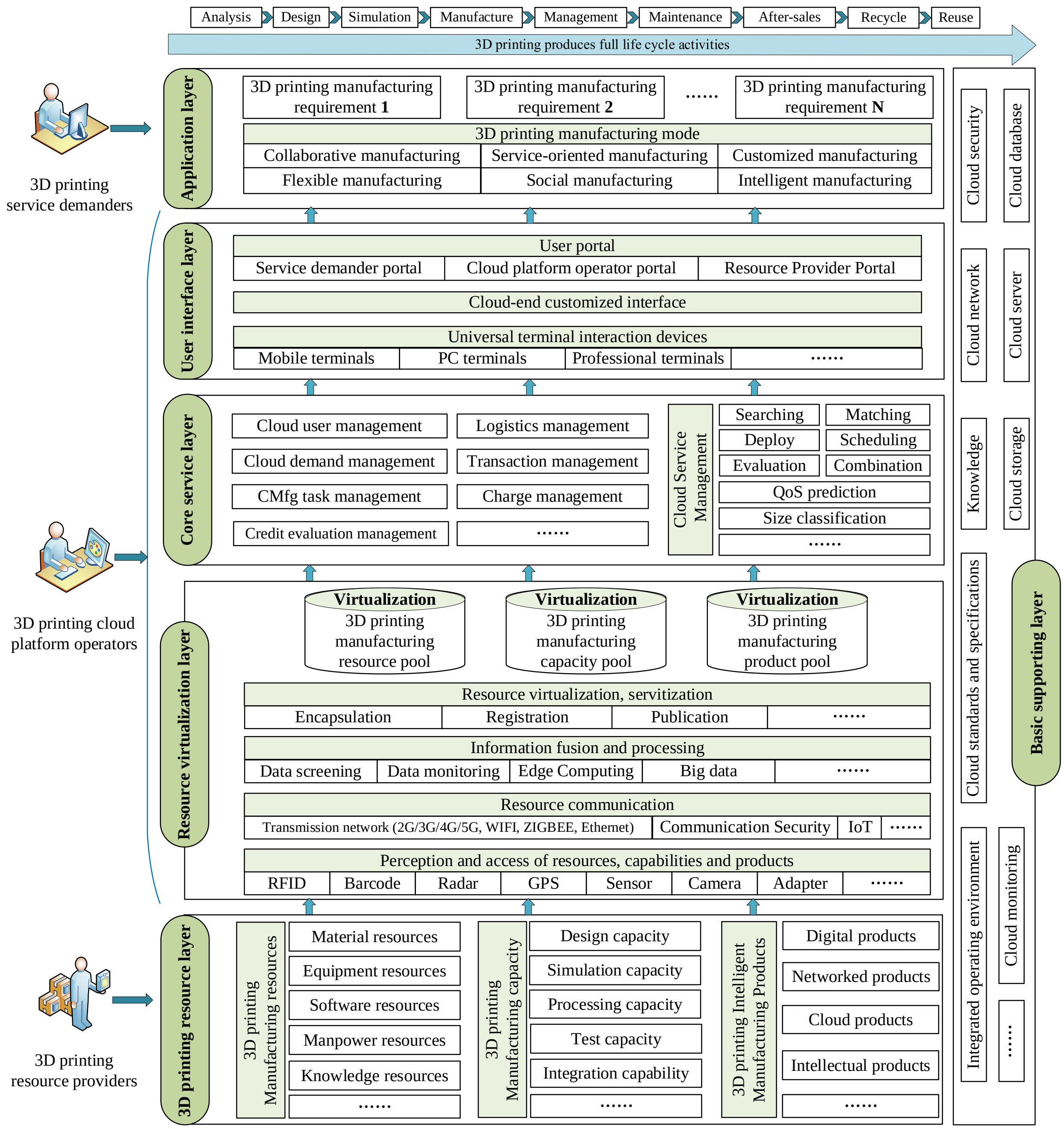

Figure XII. Improved 3D printing cloud platform architecture

Figure XII shows the improved 3D printing cloud platform architecture. It can be seen that compared with the original architecture, the improved architecture not only has richer functions and technologies and clearer processes, but also has the following internal advantages:

1) The improved architecture is more comprehensive and systematic. The new architecture not only covers the functions, technologies and equipment of the whole process of the 3D printing

CMfg system, but also includes the participation methods and processes of all users, as well as the activities of the whole life cycle of 3D printing manufacturing. The improved architecture clearly shows the main structure, macro characteristics and basic functions of the 3D printing CMfg platform, which is the basis for the development and application of the actual CMfg system.

2) The improved architecture has clear classifications, which makes the cloud platform operation process more convenient, management more efficient, and more widely used. The detailed classification of 3D printing resources is not only conducive to the subsequent virtualization, servitization, supply and demand matching and other operations of the resources, but also conducive to the better search and management of these resources in the CMfg process. For example, when searching for a 3D printing device, it is obvious that the device resource belongs to the manufacturing resource for users; when managing 3D printing slicing software resources, it is obvious that it mainly includes Cura, Slic3R and Craftware. In addition, for 3D printing manufacturing enterprises, the classification of resources can enable them to understand the advantages and disadvantages of enterprise resources, so as to increase and delete the corresponding resources in accordance with the development trend. Furthermore, the classification of management functions of the service layer makes the management of 3D printing cloud platform operators more convenient and effective. The classification of manufacturing modes makes the application of 3D printing cloud platform more diversified and enable more users to participate in the transaction of 3D printing cloud platform.

3) The improved architecture can reflect the development trend of 3D printing cloud platform. The resource layer reflects the trend towards intelligent, abstract resources. The resource virtualization layer reflects the trend towards interdisciplinary development of realization technologies. The user interface layer and application layer reflect the development trend of multi-agent and multi-manufacturing mode. The reflection of these trends in the architecture is conducive to 3D printing manufacturing enterprises to better grasp the current development trends, apply emerging technologies and absorb relevant talents timely.

Therefore, the previous 3D printing architecture is significantly improved based on the analysis of the main layers, elements, relationships, structure, functions and characteristics of architecture, providing meaningful guidance for further architecture design.

5 Current trends and future opportunities of cloud manufacturing architecture

As an architectural blueprint for the construction of CMfg service platforms, CMfg-A has received continuous attention from experts, scholars and enterprises. By combining the existing CMfg-A literature, this study believes that there are some related issues in CMfg-A that warrant in-depth study. The possible future research directions are summarized based on the analysis above.

5.1 From the perspective of the main layers

Analysing the development process of and the similarities and differences in the six main layers, this review finds that CMfg-A has some related problems in resources, technologies and applications that warrant in-depth study:

(1) Resources: In the past 10 years, manufacturing resources and manufacturing capacity have been developed and reached maturity, while the development of intelligent manufacturing products is still in the initial stage. Under the guidance of the "intelligence +" era and with CMfg as a new mode of intelligent manufacturing, the development of new intelligent manufacturing products with digitization, networking, cloudification and intelligence is undoubtedly an important direction for future research. Additionally, the diversity and complexity of resources/capacities /intelligent products in CMfg increase the difficulty of modelling, description and scheduling, which need in-depth study in the future (Liu et al., 2019b).

(2) Technologies: Over the years, scholars have focused their research on resource awareness and access. Based on traditional technologies (such as the Internet, the IoT, the Internet of vehicles, mobile Internet, satellite networks, the Tiandi integrated network, the future Internet, and edge manufacturing technology), the development and application of various sensor technologies and virtualization/servitization (fog manufacturing services) technologies under the leadership of a new generation of artificial intelligence technology also warrant future research.

(3) Applications: At present, scholars have conducted more research on the CMfg-A of traditional manufacturing industries, and they have rarely addressed emerging manufacturing fields. To promote the further development of the global manufacturing industry, architecture design in new energy, high-end equipment manufacturing, new materials and other emerging industries holds great significance. It is also important to understand the needs of specific industries and enterprises and then design personalized, specific CMfg-As.

5.2 From the perspective of elements, relationships, structures and functions

Analysing the elements, relationships, structure and functions of CMfg-A, this review finds that possible future research directions of CMfg-A include the following four aspects:

(1) Elements: The components of CMfg-A include four categories: driving elements, user elements, process elements and supporting elements. In the future, to achieve a close integration of elements and industrial innovation, user elements can be closely integrated with products, equipment, units (lines), factories (enterprises), regions, cities, industries and cross-industries based on driving factors (manufacturing full life cycle activities). At the same time, industrial systems covering full life cycle services such as supply, R&D, design, production, sales, logistics and after-sales services can be developed with the support of supporting elements to meet end-to-end requirements such as information communication, resource sharing, capability coordination, open cooperation, mutual benefits and win-win outcomes.

(2) Relationships: In the relationships of CMfg-A, the global integration and optimization of six elements (people, technology/equipment, management, data, materials, capital) and six flows (people flow, technology flow, management flow, data flow, logistics flow, capital flow) in full life cycle activities are key to the development of manufacturing companies/industries in the new era. In the future, problems such as how to realize the integration of the six elements and six flows, what technologies are needed to achieve this integration, and how to make the integration of the six elements and six flows more optimized and intelligent" will require further research and analysis in conjunction with the implementation of CMfg.

(3) Structure: The structure of CMfg-A is the integration of the interconnections and interactions between the elements, reflecting the specific logic of CMfg implementation. It is important to continuously analyse and describe the structure of CMfg-A as the scale and complexity of CMfg systems increase. Therefore, using new methods and concepts to grasp the overall structure of such systems in the future will be helpful in realizing the diversity, multidimensionality, flexibility and scalability of the architecture.

(4) Functions: CMfg-A design to realize different basic functions and application functions, and application functions determine the degree of CMfg applications. The current application functions are mainly focused on the functions of "public clouds", "private clouds" and "regional clouds". Among them, there are many applications for "private clouds" or local areas but few applications for cross-regional or large areas. The application of a CMfg system is a complex

project, and the application range and application functions of the architecture need to be expanded in the future. Designing different application functions according to different manufacturing modes (such as the collaborative manufacturing mode, service-oriented manufacturing mode, customized manufacturing mode, flexible manufacturing mode, socialized manufacturing mode and intelligent manufacturing mode) is an important direction for future research.

5.3 From the perspective of the characteristics of cloud manufacturing architecture

Analysing the characteristics of CMfg-A, this review finds that CMfg-A is undergoing a new generation of transformation, with trends of integrated development, intelligent development, innovative development and green development.

(1) Integrated development: In traditional CMfg-A design, the subjects considered by scholars are simple, and the technical basis is also considered weak. In this case, the existing technology foundation will no longer meet the design requirements of CMfg-A as the required functions of CMfg-A gradually increase. Therefore, interdisciplinary crossing and technology fusion are essential for the design of new-generation CMfg-As. The integration of emerging disciplines (such as robotics, artificial intelligence disciplines and intelligent science disciplines) and new information and communication technologies (such as big data technology, high-performance embedded simulation/edge computing technology (Ahn et al., 2019), software defined networking (SDN), 5G, blockchain technology (Aghamohammadzadeh and Valilai, 2020), digital twin technology (Zhou et al., 2020) and virtual reality/augmented reality (VR/AR) technology) is an important direction for future research.

(2) Intelligent development: Artificial intelligence technology has developed rapidly, and since the dawn of the 21st century, the manufacturing industry has entered the new "intelligence +" era. In response to the new mode in the field of manufacturing, it is crucial for CMfg-A to develop in an intelligent direction. Under the guidance of the new generation of artificial intelligence technology, building an intelligent CMfg-A that integrates people, information (cyber) space and physical space will play a vital role in the development of CMfg. Specifically, the realization of intelligent perception, cognition, learning, analysis, fusion, operation, monitoring and processing of humans/machines/objects/the environment/information in the architecture warrants further study.

(3) Innovative development: At present, scholars focus more on the CMfg-A of traditional manufacturing industries and less on that of emerging manufacturing fields. To promote the further development of the global manufacturing industry, designing CMfg-As for new manufacturing industries, such as energy conservation and environmental protection, the emerging information industry, the biological industry, new energy, new energy vehicles, high-end equipment manufacturing and new materials, holds great significance. At the same time, to realize the final implementation of CMfg-A, application demonstrations should be carried out in combination with enterprises, and innovation at all layers should be explored based on problems found and experiences summarized to improve the existing architecture and obtain more efficient and comprehensive CMfg-As.

(4) Green development: At present, the research and application of green manufacturing increasingly reflect the characteristics of globalization, and green manufacturing has become an inevitable development trend of the current manufacturing industry (Nath and Sarkar, 2017). Therefore, considering the factors of green and sustainable development in the design process of CMfg-A is a promising direction for future research. Specifically, in CMfg-A design, it is important to fully consider operations that improve resource utilization and reduce energy consumption and pollutant emissions by focusing on the time, quality, cost, service, environment, flexibility, and knowledge (TQCSEFK) goal to achieve green manufacturing.

6 Conclusion

CMfg is in line with the trend of service-oriented development in today's manufacturing industry, and its concept and related content have received attention from and recognition by academia and industry. CMfg-A research and design are related to the development of the entire CMfg system. An effective review of the research status of CMfg-A can guide future research on CMfg-A and further promote the application and implementation of CMfg. Although the relevant research on CMfg-A has been reviewed by some scholars based on many aspects, a systematic analysis of different CMfg-As is lacking in these studies; furthermore, they do not conduct in-depth analysis of the inherent nature and development trends of these architectures. Therefore, this study systematically reviews the research status of CMfg-A, obtaining the following five findings:

1) Through a descriptive analysis of the selected articles, this study understands the research status of CMfg-A from the perspectives of the distribution of the dates of publication, researchers, institutions and journals.

2) By analysing the transformation process of the six main layers, this study finds that CMfg-A resources are developing from tangible resources into intangible resources and intelligent resources. CMfg-A technology is developing from traditional cloud computing-based technology towards interdisciplinary disciplines and advanced manufacturing technology, and CMfg-A application scope is gradually expanding from traditional manufacturing industry to emerging manufacturing industry.

3) By identifying the elements, relationships, structure and functions of CMfg-A, this study finds that CMfg-A is undergoing a new generation of transformation, with trends of integrated development, intelligent development, innovative development and green development.

4) Based on the analysis of the main layers, elements, relationships, structure, functions and characteristics of architecture, the previous 3D printing architecture is improved and the advantages of the new 3D printing architecture are discussed, providing meaningful guidance for further architecture design.

5) The current trends and future research opportunities of CMfg-A are proposed based on three aspects: the development process of the main layers; the elements, relationships, structure and functions of CMfg-A; and the characteristics of CMfg-A.

This study is an achievement based on an in-depth understanding of and research on CMfg-A, and it is conducive to an in-depth understanding of the overall perspective and nature of CMfg-A. It holds guiding significance for further research on key CMfg technologies and the construction of CMfg systems with superior performance.

Appendix A. Descriptive analysis

Appendix A1, Appendix A2, Appendix A3 and Appendix A4 briefly analyse the distributions of the dates of publication, researchers, research institutions and journals of the 66 selected articles, respectively.

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