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ARTICLE

Cloud manufacturing: key issues and future perspectives

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ABSTRACT

Since the introduction of the concept of cloud manufacturing in 2010, research on it has been ongoing for more than eight years, and much progress has been made. However, existing research indicates that people lack common and comprehensive understandings of some of the key issues with cloud manufacturing such as the concept, operation model, service mode, technology system, architecture, and essential characteristics. Moreover, few studies discuss in depth the relationships between cloud manufacturing and some closely related concepts such as cloud computing-based manufacturing, Cyber-Physical Systems (CPS), smart manufacturing, Industry 4.0, and Industrial Internet. Knowledge as a core supporting factor in cloud manufacturing has rarely been discussed systematically. Also, so far there has been no standardised definition for cloud manufacturing yet. All these are key issues to be further discussed and analysed in cloud manufacturing. In order to clarify the issues above and provide reference for future research and implementation, this paper conducts a comprehensive, systematic, and in-depth discussion and analysis of the aforementioned issues in cloud manufacturing and presents an alternative definition for cloud manufacturing based on the analysis of 12 existing definitions. Future perspectives of cloud manufacturing are also discussed with respect to both academic research and industrial implementation.

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KEYWORDS
Cloud manufacturing; cloud computing; smart manufacturing; Cyber-Physical Systems (CPS); Industry 4.0; Industrial Internet

1. Introduction

In 2010, drawing inspirations from cloud computing, a new service-oriented networked manufacturing paradigm known as cloud manufacturing was introduced with the aim to solve more complex manufacturing problems and carry out larger-scale collaborative manufacturing (Li et al. 2010; Zhang et al. 2014). To date, research on cloud manufacturing has been ongoing for more than eight years and much progress has been made (Adamson et al. 2017). Today, the significance of cloud manufacturing to the manufacturing industry has been increasingly realised by more and more people, and both academic research on and industrial implementation of cloud manufacturing are undergoing rapid development (Liu, Wang, and Wang 2018a).

Researchers with different backgrounds presented their understandings of cloud manufacturing from different perspectives. Preliminary applications of cloud manufacturing to different industries have also been explored and practiced. All these significantly advance the development and implementation of cloud manufacturing. However, many key issues of cloud manufacturing need to be further discussed and consensuses need to be reached on them, including the accurate understanding of the concept (its intention, expansion and boundary), operation model, service mode, architecture, essential characteristics, etc. The relationships between cloud manufacturing and some related concepts have rarely been discussed. In addition, there are many different definitions for cloud manufacturing but there has been no standardised one yet (Fisher et al. 2018). Moreover, few works have discussed factors, problems, and stages for implementing cloud manufacturing in detail. Lacking common understandings of the concept of cloud manufacturing, lacking detailed discussions over the relationships between cloud manufacturing and some related concepts and lacking a standardised definition impede the future development of cloud manufacturing. At the current critical stage where cloud manufacturing is experiencing rapid development, it is very necessary to conduct comprehensive and in-depth discussions over the issues and present the future perspectives.

To this end, this paper carries out discussions over the critical issues with cloud manufacturing. First of all, the concept, operation model, service mode, service content, technology system, architecture, and essential characteristics of cloud manufacturing are discussed by comparing them with those of cloud computing. The relationships between cloud manufacturing and some other related concepts, including cloud computing-based manufacturing, CPS, smart manufacturing, Industry 4.0 and Industrial Internet are also discussed in detail. Then, an alternative definition of cloud manufacturing is put forward. Future perspectives of cloud manufacturing are discussed as well with respect to both academic research and industrial implementation.

The contributions of this paper are as follows. Key issues with cloud manufacturing are discussed comprehensively and in-depth and some new understandings are proposed with respect to the concept, service mode, technology system,

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essential characteristics, etc. Relationships between cloud manufacturing and cloud computing, cloud computing-based manufacturing, CPS, smart manufacturing, Industry 4.0 and Industrial Internet are clarified. Requirements for cloud manufacturing definitions and principles for defining cloud manufacturing are given and a new definition of cloud manufacturing is proposed. Moreover, future perspectives of cloud manufacturing are presented.

This rest of paper is structured as follows. The next section elaborates the relationship between cloud manufacturing and cloud computing and discusses eight key issues with cloud manufacturing. Section 3 discusses the relationships between cloud manufacturing and some related concepts. In Section 4, an alternative definition of cloud manufacturing is put forward. Section 5 discusses future perspectives of cloud manufacturing. Section 6 concludes this paper with some discussions.

2. Relationship between cloud manufacturing and cloud computing

This section discusses a number of critical issues with cloud manufacturing, including concept, operation model, service mode, service content, technology system, architecture and essential characteristics. The discussion is carried out by comparing them with those in cloud computing.

2.1. Overall relationship

First of all, it should be clear that cloud manufacturing is a concept that migrates the concept, operation model and technologies of cloud computing to manufacturing instead of simply adopts cloud computing technologies in manufacturing (Xu 2012; Wu et al. 2013a). Cloud manufacturing is therefore referred to as the 'manufacturing version of cloud computing'. The relationship between cloud manufacturing and cloud computing can overall be defined from three perspectives: resource, application and technology. As shown in Figure 1, cloud manufacturing covers cloud computing in terms of resource, application and technology. It should be noted that cloud computing has nowadays been applied to many different sectors such as healthcare, finance, education, and manufacturing, and here we focus on cloud computing itself and do not take into account its particular applications and associated resources and technologies in the above-mentioned sectors (Wang, Gao, and Fan 2015). The approach to classifying manufacturing resources in cloud manufacturing is motivated by the difference between resources in cloud manufacturing and those in cloud computing, and is compatible with the original classification: soft manufacturing resources, hard manufacturing resources, and manufacturing capabilities (Luo et al. 2013; Zhang et al. 2014). In fact, the two classifications intersect with each other (Figure 2).

2.2. Concept

Cloud computing adopts the concept of Everything-as-a-Service (i.e. XaaS), including SaaS (Software-as-a-Service), PaaS (PTlatform-as-a-Service), and IaaS (Infrastructure-as-a-Service). Borrowing the concept of cloud computing, cloud manufacturing embraces the concept of 'Manufacturing-as-a-Service (MaaS)', i.e. all manufacturing resources and manufacturing capabilities encompassed in the product lifecycle are encapsulated into services. There also exist three service models for MaaS in cloud manufacturing, i.e. Manufacturing Software-as-a-Service (MSaaS), Manufacturing Platform-as-a-Service (MPaaS), and Manufacturing Infrastructure-as-a-Service (MIaaS). The concept of 'manufacturing' in the context of cloud manufacturing should be understood broadly. It actually covers the concept of 'computing' in cloud computing. For example, the manufacturing infrastructure in cloud manufacturing includes both distributed manufacturing infrastructure (i.e. resources) from different enterprises and computing infrastructure in the cloud datacentre.

There are some differences between the XaaS concepts in cloud manufacturing and cloud computing. Firstly, manufacturing services in cloud manufacturing (including both manufacturing-oriented computing services and pure manufacturing services,

	Cloud computing	Cloud manufacturing
Resource	• General computing resources (e.g. CPU, storage)	• *General computing resources (e.g. CPU, storage)* • Manufacturing-oriented computing resources (e.g. CAX) • Pure manufacturing resources (e.g. machine tools, robots)
Application	• General computing applications	• *General computing applications* • Manufacturing-oriented computing applications • Pure manufacturing applications
Technology	• General computing resource-oriented cloud technologies	• *General computing resource-oriented cloud technologies* • Cloud technologies for manufacturing-oriented computing resources • Pure manufacturing resources, as well as many other enabling technologies (e.g. IoT)

Figure 1. Relationship between cloud manufacturing and cloud computing in terms of resources, applications and technologies.

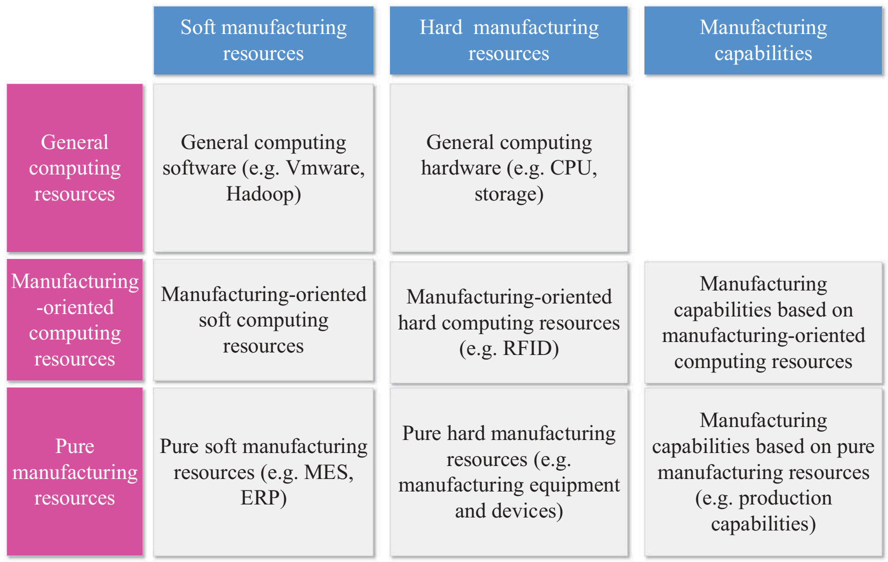

Figure 2. Intersections of two different classifications of manufacturing resources in cloud manufacturing.

especially the latter) are quite different from the general computing services in cloud computing: 1) the former are more diverse and complex, 2) the former usually take a much longer time for their execution than the latter, and 3) they have different ways of delivery, i.e. computing services in cloud computing can be delivered completely over the Internet, while manufacturing services usually need to be delivered in cyber (e.g. the Internet) and physical space (e.g. logistics) at the same time. Secondly, their aims are different. The aim of cloud computing is to satisfy consumers' requirements for computing resources and support enterprise collaboration in the cloud, while the aim of cloud manufacturing lies in two aspects: resource sharing and business collaboration among enterprises. In fact, there are overall two categories of manufacturing services in cloud manufacturing, i.e. services encapsulated from resources offered by different enterprises (i.e. resource services) and services (e.g. cloud-based Manufacturing Execution System or cloud MES, cloud-based Enterprise Resource Planning or cloud ERP, and cloud CAX software) offered in the platform by the operator (i.e. platform services). The goals of them are mainly to facilitate sharing and collaboration, respectively.

The concept constituents of them are also different (Figure 3). For cloud manufacturing, there are overall two components: cloud platform as a hub for aggregating, managing and operating manufacturing resources and enterprises as resource/service providers (in the private cloud scenario, providers are branches or departments of the same company). For cloud computing, the unique concept component is the cloud platform because no additional enterprises need to be involved as providers (see Section 2.5). Most of existing research on cloud manufacturing focuses on the cloud and regards enterprises (or other branches or departments in a private cloud) as resource nodes without delving into their internal management and operation. That is, the boundary of the concept of cloud manufacturing is currently confined to the cloud platform taking into account manufacturing resources at the same time. However, enterprises' internal management and operation can greatly affect the performance of the cloud. Simply viewing enterprises (or different branches or departments) as resource nodes obviously ignores the complexities of their internal management and operation. Therefore, there is a need to extend the boundary of the concept of cloud manufacturing and consider enterprises as complex

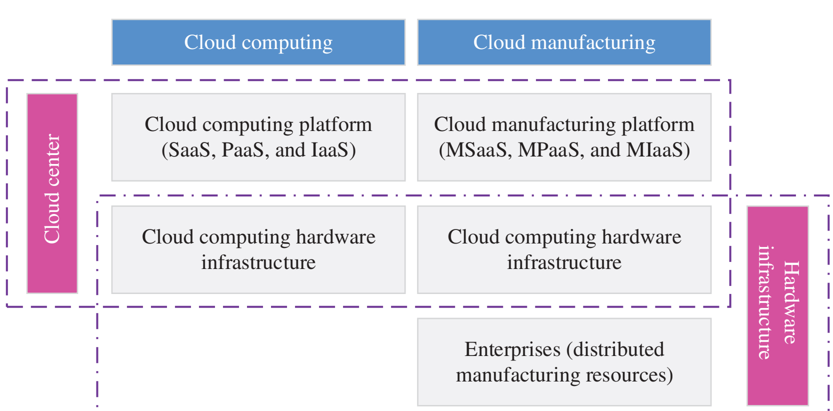

Figure 3. Comparison of concept systems of cloud manufacturing and cloud computing.

entities with complex internal management and operation instead of pure resource nodes (Liu et al. 2017b).

2.3. Operation model

To discuss operation models, it first needs to specify deployment models as different deployment models (i.e. private cloud, public cloud, community cloud and hybrid cloud) lead to different operation models. Here we focus on the first two (operation models for other deployment models can be deduced in a similar manner) (Figure 4).

- Public cloud. Irrespective of cloud manufacturing and cloud computing, there are three categories of elements in a system in terms of business model: resources, platform, and requirements. The overall operation principle for both of them is that platforms host resources and services for providing services to users to satisfy their requirements. However, the significant differences between computing and manufacturing lead to different operation models. In cloud computing, due to the relative simplicity and homogeneity of computing resources, cloud vendors usually purchase computing resources, build cloud computing platform and provide services to cloud users independently. That is, cloud providers (or infrastructure providers) act as resource providers and manager simultaneously. There are also other service providers in cloud computing (Zhang, Cheng, and Boutaba 2010). A common situation is that cloud providers provide IaaS and PaaS services and other service providers provide SaaS services to end-users based on infrastructure providers' resources (Table 1). For example, Amazon, Microsoft and Google build their datacentre independently and provide IaaS (e.g. Amazon EC2), PaaS (e.g. Microsoft Azure) and SaaS (e.g. Google Apps, Facebook) services, respectively. While in cloud manufacturing, the diversity

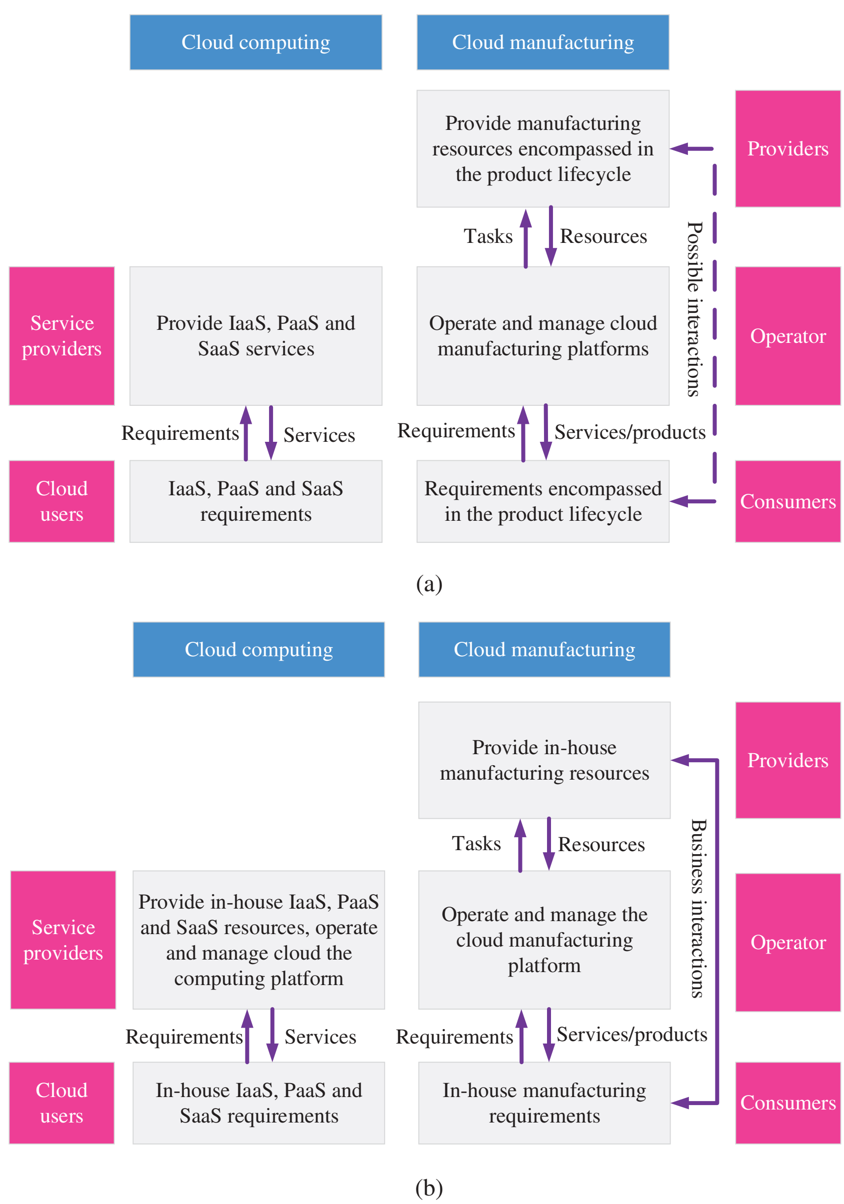

Figure 4. Comparison of operation model of public and private cloud manufacturing and cloud computing.

Table 1. Providers of resources/services at different layers in cloud computing and cloud manufacturing in the public cloud scenario.

Types of services	Cloud computing	Cloud manufacturing
SaaS	Cloud provider, service providers	Operator, providers
PaaS	Cloud provider	Operator
IaaS	Cloud provider	Providers, operator

and complexity of manufacturing resources make it impossible for the operator to purchase all manufacturing resources necessary for building a cloud manufacturing platform. As a result, cloud manufacturing has to rely on providers to provide their manufacturing resources, and the main function of the operator is to manage and operate providers' manufacturing resources. However, it should be noted that the operator may also provide some manufacturing resources such as cloud CAX, cloud ERP and cloud MES, but the majority of manufacturing resources are offered by geographically distributed enterprises and other entities (Table 1). As a result, the operation model of a public cloud manufacturing platform can be summarised as follows: manufacturing resource providers register their resources to a cloud platform and the platform operator manages and operates the platform for providing manufacturing services to consumers. For example, the CASIC manages and operates the platform INDICS and provides services to consumers (http://intl.indics.com/). As a result, the biggest difference between cloud manufacturing and cloud computing in terms of operation model is the reliance of cloud manufacturing on distributed and autonomous resource providers, which significantly increases the complexity of its operation and management (Tai, Xu, and Hu 2012). Another difference is that providers and consumers can be the same entities in cloud manufacturing as an enterprise can play both of the roles of a provider and a consumer at the same time or at different times, whereas in cloud computing, providers and consumers are usually different entities. In addition, in cloud manufacturing, the platform operator can build the cloud computing infrastructure independently or rent other cloud providers' cloud computing infrastructure or outsource the platform-building task to other companies. Software or APP developers may also be introduced in cloud manufacturing. All these stakeholders can be regarded as resource providers in cloud manufacturing.

- Private cloud. In private cloud computing or cloud manufacturing systems, the main roles involved do not change. But the difference is that all entities are from the same organisation, and only in-house manufacturing resources are aggregated in the cloud platform, and therefore are not as abundant as those in a public cloud system. For example, in cloud computing, the IT department builds a cloud computing system for providing services to other departments, while in cloud manufacturing, manufacturing resources from different departments are managed by the cloud-building department. That is, the division of roles in the private cloud manufacturing scenario is the same as that in a public cloud. This also attributes to the complexity and diversity of manufacturing resources. That fact that all stakeholders in cloud manufacturing are from the same enterprise makes it relatively simple for managing and operating a cloud manufacturing platform as their interests can be coordinated within the enterprise relatively easily (Mell and Grance 2011).

2.4. Service mode

Service mode here refers specifically to the way of providing or obtaining services. Service mode in cloud computing refers to how to provide services to consumers or how consumers access services, while service mode in cloud manufacturing includes how to provide services to both consumers and providers. In cloud computing, the service mode is on-demand self-service, i.e. a consumer can unilaterally access computing capabilities as needed automatically without human interaction with service providers (Lu and Xu 2015). In cloud manufacturing, due to the high complexity of manufacturing resources, manufacturing processes and consumers' requirements, its service mode is more complex than that in cloud computing. In cloud manufacturing, computing resources (including general computing resources and manufacturing-oriented computing resources) can generally be provided in the same way that general computing resources are provided in cloud computing. But the service mode for providing pure manufacturing resources (e.g. machine tools and robots) is relatively complicated. The reason is that during task execution processes, in addition to the operator, consumers usually need to interact with providers (e.g. to determine detailed parameters and design solutions and ownership of intellectual property (Ren et al. 2015), etc.). This means that sometimes consumers cannot obtain manufacturing services unilaterally. The service mode with direct interactions with providers is called on-demand interaction mode. Consequently, the service mode in cloud manufacturing includes both on-demand self-service and on-demand interaction service, both of which can be termed 'on-demand service'. Regarding service mode for providers, there are overall two modes: discretionary model and non-discretionary model. In the former case, a provider gives the operator full authority to operate its resources, i.e. the provider retains the ownership of its resources but transfers the right to manage and use them to the operator, whereas in the latter case, the provider registers its resources to the cloud platform but retains the ownership of its resources and the right to manage and use them. In the former case, the operator can manage and use providers' resources at will and providers do not intervene, but in the latter case, the operator needs to enquire or negotiate with providers to determine whether resources can be invoked during the transaction processes. It should be noted that resources in the latter case are usually core manufacturing resources such as machine tools and robots, and usually providers' involvement is required.

2.5. Service content

Services in cloud computing are mainly general computing resource services, while in cloud manufacturing, services include general computing resource services, manufacturing-oriented computing resource services, and pure manufacturing resource services. Services provided in cloud manufacturing can also be divided into MIaaS, MPaaS and MSaaS. From the product lifecycle perspective, services in cloud manufacturing include Design-as-a-Service (DaaS), Production-as-a-Service (PaaS), Fabrication-as-a-Service (FaaS), Simulation-as-a-Service (SIaaS), Test-as-a-Service (TaaS), Maintenance-as-a-Service (MAaaS), Management-as-a-Service (MGaaS) and Integration-as-a-Service (INaaS), etc. (Ren et al. 2015). Different types of services can be provided at different layers. Generally, hard manufacturing resources such as machine tools, robots, and 3D printers can be provided at the MIaaS layer (i.e. virtual service layer) such as Production-as-a-Service and Fabrication-as-a-Service, while software manufacturing resources such as cloud ERP, cloud MES, and many other manufacturing software (e.g. CAX) can be provided at the MSaaS layer (i.e. application layer) such as DaaS and MGaaS, and some platform-related functions can be provided as MPaaS at the MPaaS layer (i.e. global service layer) such as INaaS. If a service depends on both soft and hard manufacturing resources, and needs the support of cloud platforms as well, it can be provided across multiple layers (Coullon and Noyé 2018).

2.6. Technology system

Cloud technology is the core technology of cloud computing, and also one of the core technologies of cloud manufacturing. Cloud technology for cloud computing is a collective term for technologies pertaining to cloud computing business model and applications, including network technology, information technology, platform management and application technologies, etc. Specifically, cloud technology for cloud computing includes technologies with respect to provider requirements (such as service delivery model, service-centric issues, Quality of Service (QoS), interoperability, fault-tolerance, data management, storage and processing, load balancing, virtualisation management, and scalability), enterprise requirements (such as cloud deployment, security, cloudonomics, data governance, data migration, and business process management) and user requirements (e.g. user consumption-based billing and metering, user-centric privacy, service level agreement, and user experience) (Rimal et al. 2011). Cloud technology for cloud computing is mainly concerned with general computing resources. Similarly, cloud technology for cloud manufacturing can be defined as a collective term for technologies that are related to cloud manufacturing business model and applications, including also network technology, information technology, platform management technologies, and product, equipment, production and operation technologies, etc. (Li, Chai, and Zhang 2016). From the resource perspective, cloud technology for cloud manufacturing can be divided into three categories, including cloud technology for general computing resources, cloud technology for manufacturing-oriented computing resources, and cloud technology for pure manufacturing resources (in this sense, cloud technology for cloud manufacturing covers that for cloud computing). The former two types of cloud technology are the same, but the cloud technology for pure manufacturing resources, which is the core technology in cloud manufacturing, is different from that for general computing resources in cloud computing in some aspects. According to the classification of technologies in Li et al. (2011), cloud technologies for cloud manufacturing have some overlap with resource perception, connection and access technologies, virtualisation and servitisation technologies for cloud manufacturing resources and capabilities, construction and management, running and evaluation technologies of virtualised cloud manufacturing environments, and security technology, etc. There are some differences between the cloud technologies in cloud computing and cloud manufacturing due to the significant differences between computing resources and manufacturing resources. For example, hard manufacturing resources in cloud manufacturing are usually exclusive in use, and due to this, it is impossible for them to be used by multiple users at the same time; QoS metrics of hard manufacturing resources are also quite different from those of computing resources; resource scheduling should not always emphasise load balancing but should achieve a tradeoff between load balancing and resource quality (Liu et al. 2018b).

Apart from cloud technology, many other technologies are also required for cloud manufacturing, such as Internet of Things (IoT), Semantic Web, high-performance computing technologies, and advanced manufacturing and information technologies, etc. (Zhang et al. 2014; Tao et al. 2011). More recently, new-generation information and communication technologies (e.g. big data, mobile Internet), artificial intelligence (AI) technologies (e.g. deep learning, big data-driven knowledge engineering, Internet-based swarm intelligence) and emerging manufacturing technologies (e.g. 3D printing, intelligent robots, and intelligent manufacturing equipment) are also incorporated into the technology system of cloud manufacturing.

2.7. Architecture

There are two different types of architecture: platform architecture and system architecture. Cloud manufacturing and cloud computing have similar layered platform/system architecture. Cloud computing platform architecture consists of four layers: infrastructure layer (i.e. IaaS layer), platform layer (i.e. PaaS layer), application layer (i.e. SaaS layer), and user interface layer. Cloud manufacturing platform architecture also consists of four layers: virtual service layer (i.e. MIaaS layer), global service layer (i.e. MPaaS layer), application layer (i.e. MSaaS layer), and user interface layer. The system architecture for both cloud computing and cloud manufacturing should also include the resource layer. The correspondence and content of each layer are shown in Figure 5. By comparison, it can be found that: 1) resources encompassed at the resource layer in cloud manufacturing are more complex and diverse than those in cloud computing; 2) in comparison with the infrastructure layer (i.e. virtualisation layer) in cloud computing, the core function for the virtual service layer in cloud manufacturing includes also sensing and connecting manufacturing resources (especially hard manufacturing resources) into cloud platforms, in addition to resource virtualisation; 3) for both cloud manufacturing and cloud computing, the platform layer plays the role of an operating system by providing various software frameworks and engines for achieving

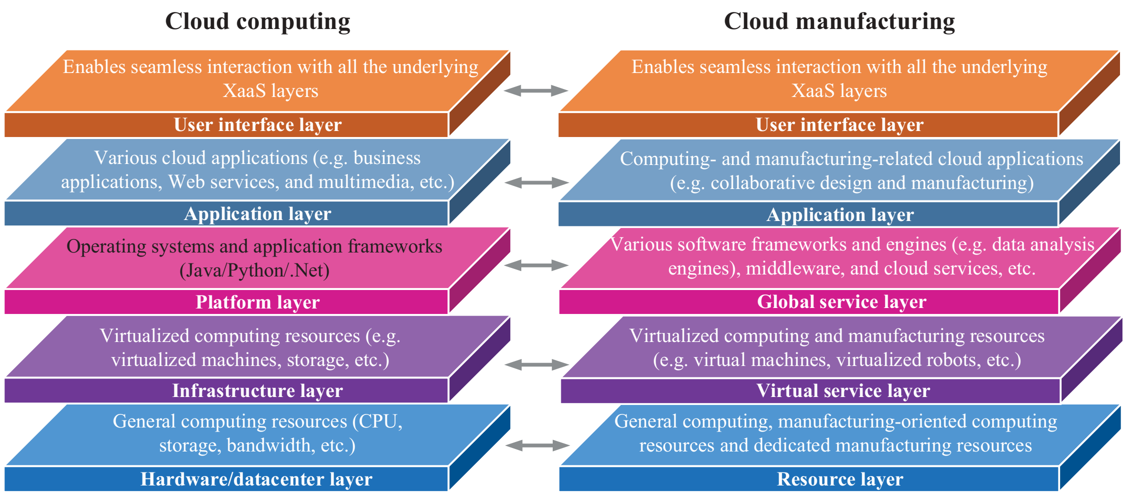

Figure 5. Comparison of architecture of cloud computing and cloud manufacturing.

functions such as shielding connections of underlying devices, performing software integration and deployment, and managing complexities of computing/manufacturing resources. Cloud manufacturing system architecture includes also other layers such as security layer, knowledge layer, and communication layer (not shown in Figure 5).

2.8. Essential characteristics

There are five essential characteristics for cloud computing, i.e. on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service (Mell and Grance 2011). Taking into account the essential characteristics of cloud computing, characteristics of manufacturing as well as the aim of cloud manufacturing, seven essential characteristics for cloud manufacturing can be identified: resource sharing, on-demand service, broad network access, ubiquitous sensing, resource pooling, rapid elasticity, and measured service. These essential characteristics characterise the existence of cloud manufacturing as a novel manufacturing paradigm and provide a benchmark for judging whether a manufacturing system is a cloud manufacturing system.

3. Relationships between cloud manufacturing and related concepts

Cloud manufacturing is a novel networked manufacturing model that draws inspirations from cloud computing. It represents a disruptive evolution and development of previous manufacturing concepts (e.g. agile manufacturing, networked manufacturing, and service-oriented manufacturing) and associated models (e.g. virtual enterprise, collaborative networks, manufacturing grid, application service provider, industrial product service system, and crowdsourcing). Existing research has already analysed and compared cloud manufacturing and the aforementioned manufacturing concepts (Zhang et al. 2011). This section focuses on comparison and analysis of cloud manufacturing and several relatively new manufacturing-related concepts, including mainly cloud computing-based manufacturing, CPS, smart manufacturing, industry 4.0 and Industrial Internet, to clarify their relationships.

3.1. Cloud manufacturing and cloud computing-based manufacturing

Cloud computing-based manufacturing refers to manufacturing that adopts cloud computing technologies in certain areas or stages of manufacturing, including typical business process management applications such as human resource management, customer relationship management, ERP and equipment data analysis (Xu 2012). Applications of cloud computing in these aspects can bring many benefits such as lowered costs, increased efficiency, enhanced integration and collaboration, and smart decision-making, etc. By contrast, cloud manufacturing is not a manufacturing model that merely uses cloud computing technologies, but comprehensive replication and extension of cloud computing concept, operation mode and technologies in manufacturing (Coullon and Noyé 2018). As cloud manufacturing applications include those based on cloud computing (e.g. cloud-based software applications provided by the operator), the cloud manufacturing concept actually covers the concept of cloud computing-based manufacturing. But the reverse is not true, i.e. strictly speaking, cloud computing-based manufacturing is not and also cannot represent cloud manufacturing. From the technology perspective, cloud computing is just one of the many underpinning technologies for cloud manufacturing. As a result, cloud computing-based manufacturing can be regarded as a subset of cloud manufacturing.

3.2. Cloud manufacturing and CPS

Cloud manufacturing is a manufacturing paradigm aiming at providing on-demand manufacturing services. CPS are the integration of computation, networking, and physical processes, in which computation and physical processes monitor and impact each other through networks, forming a feedback loop. CPS have found applications in a wide range of areas such as transportation, smart home, robotic surgery, aviation, defence, manufacturing, etc., and its application in production or manufacturing leads to Cyber-Physical Production Systems (CPPS) (Wang, Torngren, and Onori 2015). It is easy to see that cloud manufacturing and CPS are not concepts in the same dimension: the former are a manufacturing model while the latter are a technology. Regarding their relationship, it is generally acknowledged that CPS are one of the enabling technologies for cloud manufacturing. However, unlike IoT which is designated specifically to sense and connect hard manufacturing resources into the cloud manufacturing platform, the function of CPS in cloud manufacturing is relatively less discussed (Liu et al. 2017a).

From a macroscopic perspective, a cloud manufacturing system can overall be regarded as a huge, generalised CPS with the physical part being distributed manufacturing resources and systems from different enterprises involved and cyber part being the logical mapping of the physical part in the cloud. The cloud platform collects data of physical manufacturing resources and systems in real time, optimises the physical manufacturing systems and controls the system remotely as necessary. However, technologically, cloud technology (especially virtualisation and service-oriented architecture) is a core technique of cloud manufacturing, whereas CPS does not emphasise the involvement of cloud technology. On the other hand, a cloud manufacturing system does not necessarily involves feedback control over hard manufacturing resources (e.g. machine tools, robots) from the cloud (Liu et al. 2017a). As a result, only a cloud manufacturing system with resource feedback control can be regarded as a cloud-based CPS.

In fact, not all parts of a cloud manufacturing system have to be implemented as a CPS, because 1) from the perspective of requirements, there are many different requirements from consumers, and if an open-loop system can meet consumers' requirements, then it does not need to be implemented as a close-loop system; 2) from a business operation perspective, cloud manufacturing platforms do not always have the right to access and control manufacturing resources from different enterprises as they may set different access permissions for their resources; 3) from the manufacturing resource perspective, some legacy equipment does not always have the conditions and interfaces to be controlled directly from the cloud; and 4) pure computing processes cannot be implemented as CPS as no physical processes are involved. Despite of the fact above, some parts of a cloud manufacturing system are CPS. In this sense and from a microscopic point of view, a cloud manufacturing system involves numerous CPS with different granularities at different levels.

3.3. Cloud manufacturing and smart manufacturing

When it comes to the relationship between cloud manufacturing and smart manufacturing, the first question that comes into one's mind is: is cloud manufacturing a smart manufacturing paradigm? In order to answer this question, we should first be clear about what smart manufacturing is. NIST defined smart manufacturing as 'fully integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply network, and customer needs.' (Kang et al. 2016; https://www.nist.gov/programs-projects/smart-manufacturing-operations-planning-and-control-program). Let's check the characteristics of cloud manufacturing to see whether it confirms to the definition of smart manufacturing above. Firstly, cloud manufacturing is a manufacturing paradigm that supports ubiquitous resource sharing and efficient business collaboration by aggregating and integrating distributed manufacturing resources from different enterprises into cloud platforms in the form of manufacturing services. Secondly, the aim of cloud manufacturing is to meet consumers' unpredictable, increasingly individualised requirements by allowing them to be involved in the product lifecycle. Thirdly, conditions of manufacturing resources, systems and processes within different factories and across supply networks are monitored in real-time in cloud manufacturing. It is easy to see that the characteristics of cloud manufacturing are in line with the definition of smart manufacturing. On the other hand, eight key and representative technologies for smart manufacturing, including CPS, IoT, cloud computing, big data, additive manufacturing (3D printing), sensors, energy saving, and holograms are identified (Kang et al. 2016). According to the latest concept of cloud manufacturing, most of the technologies (especially the first six ones) are required for cloud manufacturing. As a result, we can now come to the conclusion that cloud manufacturing is a smart manufacturing paradigm.

3.4. Cloud manufacturing, Industry 4.0 and Industrial Internet

First of all, it should be noted that cloud manufacturing, Industry 4.0 and Industrial Internet are complex concepts that evolve over time, and moreover, different people with different backgrounds have different understandings of them, and thus it is very difficult to define their relationship exactly. As a result, here we only conduct a rough comparative analysis of them. Our comparison is based on concept of Industry 4.0 defined in the final report of the Industry 4.0 Working Group (Kagermann et al. 2013) and the concept of Industrial Internet defined in the technical report of General Electric (Evans and Annunziata 2012).

Cloud manufacturing is a service-oriented networked manufacturing paradigm, Industry 4.0 stands for the fourth industrial revolution (Liu and Xu 2017), and Industrial Internet represents the third wave after the first two waves, i.e. the Industrial Revolution and the Internet Revolution. It is easy to see that they were proposed from different perspectives, which are 'advanced manufacturing models', 'industrial revolution', and 'industrial revolution plus Internet revolution', respectively. Cloud manufacturing and Industry 4.0 focus on manufacturing only, but the latter takes more manufacturing-related issues into account than the latter (Kagermann et al. 2013; Liu and Xu 2017). In contrast, Industrial Internet applies to many industries (including the manufacturing industry). In this sense, the scope of the concept of Industrial Internet is broader than that of Industry 4.0, which is in turn broader than that of cloud manufacturing. Although being proposed from different perspectives and with different concept constituents, aims and focuses, they are all manufacturing or industrial concepts that utilise emerging Internet, computer, and information technologies such as IoT, CPS, cloud, and big data to unleash the full potential of industrial production.

They have different origins and purposes. The term 'cloud manufacturing' was initially coined by Chinese scholars and there was a two-stage national 863-plan project on cloud manufacturing. The initial simple purpose of cloud manufacturing is to increase resource utilisation and collaboration efficiency. This is because China has the most abundant manufacturing resources with different levels and therefore how to effectively fully utilise these resources becomes an important problem. Industry 4.0 was initiated by the German government, together with some academic research institutes and private business associations. The ultimate aim of Industry 4.0 is to safeguard a sustainable competitive advantage for the German manufacturing industry. This is because Germany plays a leading role in research and development of its industry and wants to maintain this role in the future without being affected by technological changes. The concept of Industrial Internet was initially put forward by GE and the Industrial Internet Consortium (IIC) was formed in 2014 with the support of GE, AT&T, Cisco, Intel and IBM. Its purpose is to catalyse and coordinate priorities and enabling technologies in industry, academia and governments around the Industrial Internet.

Their basic ideas are different, which are reflected by the key elements in their concepts and technologies. The core elements in the concepts of cloud manufacturing, Industry 4.0 and Industrial Internet are 'services (i.e. manufacturing cloud services)', 'smart factories' and 'intelligent machines', and their core technologies are cloud technology, CPS, and advanced analytics, respectively. Their core concepts and technologies reflect their basic ideas. The basic idea of cloud manufacturing is to enable on-demand access to a shared pool of configurable manufacturing services through establishment of different types of manufacturing clouds (e.g. private cloud, public cloud) that aggregate and integrate manufacturing resources and manufacturing capabilities from different manufacturing enterprises. The basic idea of Industry 4.0 is to achieve smart production by means of building CPS-based smart factories and as well as realising the horizontal integration and end-to-end integration. The basic idea of Industrial Internet is to improve machine and system performances by means of big data and advanced analytics-based intelligent decision-making.

There are some differences in their concept systems. The concept system of Industry 4.0 encompasses both intra-enterprise and inter-enterprise aspects, which are vertical integration (smart factory) and horizontal integration (CPS platform), respectively. The concept of cloud manufacturing also includes the aforementioned two aspects, which are realised in the form of private cloud and public cloud (or community cloud), respectively. In contrast, in Industrial Internet, only intelligent machines and people are emphasised without introducing concepts like smart factory, but it emphasises the importance of establishment of system platforms that enable firms to build specific applications upon a shared framework/architecture. As a result, they all emphasise the significance of establishment of platforms. So far, three industrial Internet platforms have already been built, which are CASIC's INDICS (http://intl.indics.com/), Siments's MindSphere (https://siemens.mindsphere.io/), and GE's Predix (https://www.predix.io/), which are based on the concepts of cloud manufacturing, Industry 4.0, and Industrial Internet, respectively.

There are some differences in their themes and objectives. The main aim of cloud manufacturing is to achieve full resource sharing and highly efficient enterprise collaboration. In cloud manufacturing, manufacturing resources and manufacturing capabilities within a value chain or across different value chains (or value networks) are aggregated into cloud platforms as manufacturing cloud services so that consumers can have access to manufacturing services in an on-demand manner and individualised, flexible, scalable, and configurable production and services can be realised. The theme of Industry 4.0 can be summarised as smart factory and smart production. It focuses on production processes and aims to achieve decentralised enhanced control so as to achieve highly flexible, individualised and digital production and services. Industrial internet aims to realise an open and global industrial network and achieve the integration of communication, control and computation, focusing on the design and service stages and emphasising improvements of production equipment management and services through technologies such as IoT and big data. Overall, Industry 4.0 focuses more on the 'hard' aspect such as production, Industrial Internet emphasise more the 'soft' aspect such as analytics and services, while cloud manufacturing focuses more on the cloud-based integration, management and operation, which can also been regarded as the 'soft' aspect.

Integration and networking are their common characteristic. Industry 4.0 is characterised by three types of integration: vertical integration together with networked manufacturing systems, horizontal integration through value networks, and end-to-end digital integration of engineering across the value chain of a product lifecycle. In Industry 4.0, all instances involved in value creation are networked to enable the availability of all relevant information in real-time. Industrial Internet is characterised by the integration and networking of intelligent machines, facilities, fleets and networks and people, which enables collection and analysis of the data of them and identification of the potential of production and services so as to achieve improved system performance. In cloud manufacturing, all manufacturing resources and manufacturing capabilities are networked and integrated into cloud platform as manufacturing cloud services through technologies such as IoT, virtualisation, and service-oriented technologies, which enables on-demand access.

The major means for achieving their aims are also different. Cloud manufacturing aims to achieve cloud service-based resource sharing and collaboration based on the cloud platform that pools resources of enterprises from an industry or different industries using cloud technology in combination with other technologies such as IoT and CPS. The means for achieving smart production for Industry 4.0 are to realise the integration of smart products with production equipment, integration of networked manufacturing systems, and horizontal integration across different factories based on CPS. Industrial Internet is able to boost security and reliability of manufacturing equipment, reduce energy and material consumption and maintenance cost, and at the same time, increase flexibility and smartness of production processes and reduce requirements for human labour by using data and information from the entire industry.

They share many common technologies for their research and implementation, including, typically, IoT, CPS, cloud, big data and its analytics, AI, security, integration, robot, simulation, additive manufacturing, etc. However, the significance, functions and essences of these technologies in them are somewhat different. For example, cloud technology in cloud manufacturing is manufacturing-oriented cloud technology, which is usually different the cloud computing technology in Industry 4.0 and Industrial Internet. CPS are a core technology for Industry 4.0, but cloud manufacturing does not necessarily rely on CPS technology, although implementing all appropriate parts as CPS are critical for fully achieving its aim (see Section 3.2). Moreover, in the context of cloud manufacturing, CPS are closely related to manufacturing cloud technology (Liu et al. 2017a). Industrial Internet does not emphasise CPS so much. Instead, it emphasises intelligent machines, which actually paves the way for realising CPS. Industrial Internet emphasises also advanced analytics, which is actually of great significance to all of them. In fact, the discussion above just reflects their initial idea for adoption of technologies. What is truly important is what technologies are adopted for their implementation. According to the current trend, it can be predicted that they will converge in terms of technology adoption for implementation in the future instead of confining to the above-mentioned ones. For example, in the future, manufacturing resources and manufacturing capabilities (intelligent machines and people) from different factories are pooled into the cloud manufacturing platform, and in combination with CPS, advanced analytics and AI, etc., intelligent manufacturing services can be provided.

3.5. Cloud manufacturing and other related concepts

Apart from the concepts discussed above, there were also many other related concepts, such as e-manufacturing, ubiquitous manufacturing, wireless manufacturing, and social manufacturing, whose relationships with cloud manufacturing should also be discussed, and with these discussions, the concept of cloud manufacturing could be made clearer.

E-manufacturing is an Internet-based concept for manufacturing that covers the whole range of online manufacturing activities for products and services from production design, production control to sale services. E-manufacturing, characterised by digitisation, globalisation, mobility, collaborative work, and immediacy, emphasises manufacturing operated in integration with Internet technology (Cheng 2005; Cheng and Bateman 2008; Cheng, Pan, and Harrison 2001). There are some similarities between cloud manufacturing and e-manufacturing. For instance, both of them cover many activities for products and services involved in the product life cycle, employ Internet technology as a major enabling technology, and share some common characteristics. However, there are some major differences between them in terms of backgrounds, concept intension, enabling technologies, operation model, and so on. As mentioned above, the background for introducing cloud manufacturing was that many new technologies (especially cloud computing, IoT, and virtualisation and servitisation of hard manufacturing resources) and new requirements (such as more complex manufacturing issues, larger-scale manufacturing collaboration, more emphasis on green and low-carbon manufacturing, and more emphasis on services and intelligence) for the manufacturing industry emerged. Cloud manufacturing, as its name implies, adopt cloud technology as one of its core technologies, plus many other technologies such as IoT, SOA, AI, for creating and providing on-demand manufacturing cloud services to consumers. In order to be commercially viable, it draws on the business model of cloud computing. But e-manufacturing was proposed with a different background (because e-manufacturing was introduced much earlier than cloud manufacturing) and had a different set of technologies. Moreover, there was no specific operation model for e-manufacturing.

Ubiquitous manufacturing is an application of ubiquitous computing in the manufacturing sector featuring a 'design anywhere, make anywhere, sell anywhere, and at any time' paradigm that grants factories an unlimited production capacity and permanent manufacturing service availability (Chen and Tsai 2017). Like cloud manufacturing, ubiquitous manufacturing also emphasises manufacturing services. So far, there have been no organisational methods and information and communication technology infrastructures for implementing ubiquitous manufacturing. Technologies for ubiquitous manufacturing include ubiquitous sensors and sensing technologies, such as radio frequency identification (RFID), auto ID, virtual reality, CPS, GPS, and Wi-Fi, Web services, IoT, real-time decision-making and even social networks. From the above description, we can find that the concept of ubiquitous manufacturing is similar to cloud manufacturing (in fact, in many studies ubiquitous manufacturing and cloud manufacturing were not differentiated). However, in terms of concept description (e.g. technologies, aim, etc.), cloud manufacturing can roughly be regarded as a special type of ubiquitous manufacturing as it enables ubiquitous, convenient, on-demand network accesses to a shared pool of configurable manufacturing resources. There are some subtle differences that should be pointed out. For example, cloud manufacturing typically deploys cloud services through the Internet, whereas ubiquitous manufacturing does not necessarily rely on the Internet. In fact, ubiquitous manufacturing can be roughly divided into the applications of ubiquitous technologies and the widespread deployment of manufacturing facilities. The former applications are typically confined to in-factory operations or logistics and thus do not necessarily involve the Internet. Wireless manufacturing is another concept for advanced manufacturing, which relies substantially on wireless devices such as RFID or Auto ID (automatic identification) sensors, and wireless information/communication networks (Huang, Wright, and Newman 2009). Wireless manufacturing can typically benefit shop-floor applications such as product assembly, part fabrication, mass customisation, manufacturing asset management and maintenance, and product lifecycle management. Wireless manufacturing is able to achieve real-time traceability and visibility while minimising the total cost by deploying smart objects in manufacturing environments. Hence, wireless manufacturing is a subset of ubiquitous manufacturing, and the corresponding technologies are also enabling technologies for cloud manufacturing.

Social manufacturing is another manufacturing concept and paradigm that emphasises use of CPS and social media in manufacturing. It is a cyber-physical-social-connected and service-oriented manufacturing paradigm that drives distributed production service providers (PSPs) to self-organise into dynamic resource communities (DRCs) through social networks, provides the production- and product-related services to prosumers, and collaborates with prosumers through cyber-physical-social systems (CPSS) (Jiang, Ding, and Leng 2016). Social manufacturing is able to promote socialised resources utilisation, social community-based resource self-organisation, cyber-physical-social interconnection, social media-based communication and social business relationship management, etc. Cloud manufacturing and social manufacturing are named from the perspectives of technology and scope, but they share some common aspects such as adoption of CPS, service-oriented nature, support for large-scale collaboration, emphasis of resources and services throughout product life cycle, and emphasis of customer involvement, etc. There are also some differences between them. For instance, cloud manufacturing emphasises encapsulation of all manufacturing resources and capabilities in the product life cycle into cloud services, and aggregation of them into the cloud platform for centralised management, but it does not emphasise the use of social media so much, although it provides good support for this with the construction of cloud platforms. In fact, it is very difficult to clearly state their relationships, but overall we can say that cloud manufacturing facilitates realisation of social manufacturing (at least some aspects) because cloud manufacturing as a well-developed concept for manufacturing has sufficient flexibility and adaptability.

4. Knowledge in cloud manufacturing

Cloud manufacturing is a knowledge-based intelligent manufacturing paradigm. Knowledge plays a key role in enabling intelligence of cloud manufacturing, and thus can enhance manufacturing operations instead of increasing the complexity in cloud manufacturing. More specifically, knowledge is required for many activities and processes across different phases in the life cycle of services, including those in 1) the phase of service generation (e.g. perception, access, virtualisation and servitisation of manufacturing resources and capabilities), 2) the phase of service management and operations (e.g. service search, matching, composition, scheduling, monitoring, and fault-tolerance), and 3) the phase of service application across product life cycles in different industries (e.g. the design phase in the machine tool industry). The concept of knowledge in cloud manufacturing is generalised and should be understood broadly, including various data, information, rules, models, algorithms, and standards, etc.

In cloud manufacturing, all manufacturing resources, soft or hard, and manufacturing capabilities need to be perceived and connected to the cloud platform, and then virtualised and transformed into cloud services for facilitating service management and applications. Activities involved in this process include identification of manufacturing resources and capabilities using technologies such as RFID and IoT, virtualising and encapsulating them into services, resource and capability modelling and digital description, and construction of cloud services. Related knowledge includes information about resource (include interface information, sensor information and abilities descriptions), rules for classifying resources and capabilities, rules for accessing resources, standards for equipment connection and data transmission, algorithms for data management and analytics, approaches and languages for service modelling and description, etc.

After creation, services need to be properly managed and operated for better satisfying consumers' requirements. Service management and operations in cloud manufacturing concern mainly user management (e.g. registration, role, preference, credit, cooperation relationships, and privilege), task management (e.g. task publication, decomposition, and scheduling), and service management (e.g. service search and matching, transaction, composition, scheduling, evaluation, billing, and fault-tolerance). Knowledge plays different roles in all the management processes mentioned above. Some of the activities of service management and operations require support of knowledge for their being able to be carried out, while some other activities are enhanced with the support of knowledge (such as higher efficiencies and stronger capabilities). For example, for service management, metrics, rules, and algorithms for service scheduling are required for performing scheduling smoothly (Liu et al. 2018b) (all of the metrics, rules, and algorithms are knowledge that supports service management) (Hu et al. 2012). Task processing is also a knowledge-intensive process. For example, knowledge-based semantic reasoning engine is needed for task decomposition, i.e. how to divide a task into subtasks with different granularities taking into account characteristics of different services. Overall, knowledge in cloud manufacturing can be classified into five categories: domain knowledge, reasoning knowledge, task knowledge, case knowledge, and service description knowledge, etc. (Hu et al. 2012). In order to provide better support for management and operations of manufacturing clouds, knowledge base management systems need to be built (Zhao et al. 2017). Ontology provides an effective method for knowledge representation (Liu, Xu, and Zhan 2014), which enables the system to have reasoning ability for solving complex problems (Yin, Ding, and Wu 2015).

Finally, product life-cycle applications in different industries in cloud manufacturing also require support of knowledge, which cover activities such as argumentation, design, production planning, fabrication, simulation, etc. Because activities in this phase depend on service management and operations, knowledge for service management and operations is undoubtedly needed. In addition to this, domain-specific knowledge is more necessary because this phase focuses on specific applications (such as process planning, production planning, machining, etc.) in different industries.

Knowledge representation, acquisition, reasoning are important issues of knowledge manipulation (Hu et al. 2013). Semantic Web technology has been widely used in knowledge representation, which greatly facilitates knowledge integration, management, access and re-use. Ontology is an important tool for knowledge representation, organisation, handling, and retrieval. Ontology modelling and ontology annotation are prerequisites for ontology-based knowledge applications. OWL and SWRL are important tools for semantic and logic representation of knowledge. In order to apply knowledge, it first needs to be acquired, which can be non-automatic and semi-automatic. Knowledge reasoning is an important process for knowledge applications that enables intelligence of a cloud manufacturing system and produce new knowledge. With the support of ontology, knowledge reasoning can be semantic, which significantly enhances the effect of knowledge applications.

5. Revisit to the definition of cloud manufacturing

This section presents an alternative definition for cloud manufacturing based on NIST's definition for cloud computing taking into account particular characteristics of cloud manufacturing.

First of all, we give the requirements of cloud manufacturing definitions and principles for defining cloud manufacturing:

(1) The following essential characteristics of cloud manufacturing should be reflected in the definition: 1.1 cloud manufacturing is a manufacturing model; 1.2 the tri-party (providers, operator, and consumers) operation model; 1.3 the core characteristic of cloud manufacturing – resource pooling.
(2) Underpinning technologies for implementing cloud manufacturing and associated implementation schemes should not be defined and explained in the definition (Adamson et al. 2017). The definition of cloud manufacturing should provide a high-level description of cloud manufacturing without delving into technological details for implementation as the essence of cloud manufacturing does not change but technologies may change.
(3) Effects resulting from implementation of cloud manufacturing in terms of productivity, utilisation, agility, economy, environment, etc., should not be mentioned or highlighted in the definition (Adamson et al. 2017). These effects should be mentioned but in other places instead of in the definition.

According to the aforementioned requirements and principles, existing definitions can be analysed as follows (Table 2):

According to the analysis, we propose a cloud manufacturing definition as follows:

> *A model for enabling aggregation of distributed manufacturing resources (e.g. manufacturing software tools, manufacturing equipment, and manufacturing capabilities) and ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing services that can be rapidly provisioned and released with minimal management effort or service operator and provider interaction.*

6. Future perspectives

This section discusses future perspectives of cloud manufacturing with respect to academic research and industrial implementation.

6.1. Academic research

Many issues to be addressed in the future have been presented and discussed in some previous studies, such as standardisation, monitoring and control systems (e.g. cloud close-loop manufacturing), knowledge and information management and sharing, multi-cloud integration, distributed manufacturing simulation, security, business model (e.g. utility equilibrium for different types of participants, intelligent property, cloud service brokers), integration of enterprise systems with the cloud, sustainability, and cloud manufacturing adoption (i.e. populating the cloud), etc. (Adamson et al. 2017; He and Xu 2015). In the following, issues that have not mentioned are identified and discussed.

- Classification and hierarchy of technologies in cloud manufacturing. Many technologies are required for implementation of cloud manufacturing. Effective integration of the technologies is, however, a great challenge (Wang et al. 2012). In order to facilitate its implementation, the technologies should be classified according to their relevance and maturity. Presenting numerous technologies without any classification provides little insights into development and implementation of cloud manufacturing. However, so far, few studies have answered questions like which technologies are core technologies that are indispensable for implementation of cloud manufacturing (e.g. IoT, cloud technology and security), which are key technologies that are critical for cloud manufacturing implementation but not indispensable (e.g. big data, CPS, and AI), and which are general enabling technologies that are mainly used for enriching the function of a cloud manufacturing system (e.g. complex network, agent technology) to make it more complete (Liu, Wang, and Wang 2018).
- Degree of involvement of enterprises in cloud manufacturing. According to the proportion of businesses enterprises do in the cloud platform and the degree of the integration of enterprise systems with cloud systems, enterprises' participation in cloud manufacturing can be at different levels (e.g. junior (≤20%), middle (≥50%) or senior (≥80%)). For example, at the junior level, an enterprise registers a small proportion of resources to the cloud platform and correspondingly, only a small proportion of revenue comes from the cloud business, and moreover, only some of its information systems and manufacturing resources are integrated with the cloud. In the future, index systems need to be developed to evaluate the level at which enterprises participate in cloud manufacturing.
- Requirements and architecture of enterprises in cloud manufacturing. When enterprises adopt or participate in cloud manufacturing, some changes to internal management and operation need to be made to adapt to this new manufacturing paradigm. In the future, requirements for enterprises in cloud manufacturing with different participation levels need to be investigated, and associated enterprise architecture needs also to be explored (Liu et al. 2017b). Currently, smart factory is an

Table 2. Existing cloud manufacturing definitions and associated analysis.

No.	Definitions	Analysis
1	A networked manufacturing model that provides various on-demand manufacturing resources (manufacturing cloud) according to consumers' requirements through networks and cloud manufacturing platforms (Li et al. 2010)	Reflects 1.1, does not reflect 1.2, and partly reflects 1.3. Confirms to 2 and 3
2	Cloud manufacturing is an extension and development of cloud computing and existing advanced manufacturing concepts and technologies such as networked manufacturing, application service provider, manufacturing grid. It integrates existing information-based manufacturing technology, and cloud computing, Internet of Things, service-oriented technology, high-performance computing technology, and intelligence science and technology, virtualises and servitises various manufacturing resources and manufacturing capabilities, pools them together, and intelligently manages and operates them in a unified and centralised way to achieve win-win for all parties and ubiquitous and efficient sharing and collaboration, so that safe and reliable, quality and cheap manufacturing services encompassed in the entire product lifecycle can be provided to consumers anytime in an on-demand way via networks and cloud manufacturing service platforms (Li et al. 2011)	Reflects indirectly 1.1 and 1.2, reflects 1.3, does not confirms to 2 and 3
3	A model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g. manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction (Xu 2012)	Reflects 1.1 and 1.3, does not reflect 1.2, confirms to 2 and 3
4	Cloud manufacturing implies an integrated cyber-physical system that can provide on-demand manufacturing services, digitally and physically, at the best utilisation of manufacturing resources. It aims at offering a shared pool of resources such as manufacturing software tools, manufacturing facilities, and manufacturing capabilities. However, cloud manufacturing is more than simply deploying manufacturing software applications in the computing cloud. Besides data storage and virtual machines, the physical resources integrated in the manufacturing cloud are able to offer adaptive, secure and on-demand manufacturing services over the Internet of Things, including work cells, machine tools, robots, etc. (Wang et al. 2014)	Does not reflect 1.1 and 1.2, reflect 1.3, confirms to 2 and 3
5	Cloud-Based Design and Manufacturing refers to a product realisation model that enables collective open innovation and rapid product development with minimum costs through a social networking and negotiation platform between service providers and consumers. It is a type of parallel and distributed system consisting of a collection of inter-connected physical and virtualised service pools of design and manufacturing resources (e.g. parts, assemblies, CAD/CAM tools) as well as intelligent search capabilities for design and manufacturing solutions (Wu et al. 2012)	Does not reflect 1.1, reflects 1.2 and 1.3, confirms to 2 and 3
6	Cloud-based design and manufacturing refers to a product development model that enables collective open innovation and rapid product development with minimum cost through social networking and crowd-sourcing platforms coupled with shared service pools of design, manufacturing resources and components (Schaefer et al. 2012)	Does not reflect 1.1, reflect indirectly 1.2, reflects 1.3, confirms to 2 and 3
7	Cloud-based design and manufacturing (CBDM) refers to a service-oriented product development model in which service consumers are able to configure products or services as well as reconfigure manufacturing systems through Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), Hardware-as-a-Service (HaaS), and Software-as-a-Service (SaaS) in response to rapidly changing customer needs. CBDM is characterised by on demand self-service, ubiquitous access to networked data, rapid scalability, resource pooling, and virtualisation. The types of deployment models include private, public, and hybrid clouds (Wu et al. 2013b)	Does not reflect 1.1 and 1.2, reflects indirectly 1.3, does not confirm to 2, confirms to 3
8	Cloud manufacturing (CM) is a customer-centric manufacturing model that exploits on-demand access to a shared collection of diversified and distributed manufacturing resources to form temporary, reconfigurable production lines with enhanced efficiency, reduced product lifecycle costs, and allow for optimal resource loading in response to variable-demand customer generated tasks (Wu et al. 2013a)	Reflects 1.1, reflects indirectly 1.2, reflects 1.3, confirms to 2, does not confirm to 3.
9	Cloud Manufacturing is a networked manufacturing model in which locally and globally distributed manufacturing resources for the complete product life-cycle are made available by providers for satisfying consumer demands, and are centrally organised and controlled as manufacturing Cloud services. The model supports unified interaction between service providers and consumers, for trading and usage of configurable resources/services, as well as dynamic and flexible cooperation and collaboration in multi-partner manufacturing missions. Distinct characteristics for the use of services are that they are scalable, sold on demand, and fully managed by the provider (Adamson et al. 2017)	Reflects 1.1 and 1.2, reflects indirectly 1.3, confirms to 2 and 3, but it is not accurate to say that the use of cloud services are fully managed by the provider
10	Smart cloud manufacturing is a ubiquitous network-based digital, networked, and intelligent technological means that integrates deeply four categories of technologies, including emerging manufacturing technologies, emerging information technology, intelligent science and technology, and manufacturing application technologies. It establishes consumer-centric smart service clouds (i.e. networks) for manufacturing resources and manufacturing capabilities that enable consumers to access smart manufacturing resources and manufacturing capabilities anytime, anywhere in an on-demand way through smart terminals and smart cloud manufacturing platforms. It autonomously sense, connect, coordinate, learn, analyse, recognise, determine, control and execute system-wide man, machines, materials, environment, and information that encompassed in the product lifecycle, drives the integrated optimisation of associated people/organisation, operation management, technologies/devices (three elements) and information flow, material flow, finance flow, knowledge flow and service flow (five flow) and establishes a new ubiquitous network-based, customer-centric networked, servitised, collaborative, individualised (customised), flexible, social smart manufacturing model that fuses man, machines and materials, which enables efficient, quality, cost-effective, green, and flexible product manufacturing and consumer service and increased competitiveness of manufacturing enterprises (Li, Chai, and Zhang 2016)	Reflects 1.1, does not reflect 1.2, reflects indirectly 1.3, does not confirm to 2 and 3
11	Cloud manufacturing is a service oriented manufacturing model that virtualises manufacturing resources and capabilities into on-demand services accessed through the manufacturing cloud. This transforms manufacturing supply lines to become temporary, and provide greater flexibility and scalability resulting in increased resilience and sustainability throughout the manufacturing process. Cloud manufacturing is a multi-tenant, intelligent, knowledge based platform that can provide sustainable solutions throughout the product and process life cycle via effective collaboration, data mining, and communication across a network of developers, manufacturers and consumers (Fisher et al. 2018)	Reflects 1.1, does not reflect 1.2, reflects indirectly 1.3, does not confirm to 2 and 3
12	Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g. application service providers, agile manufacturing, networked manufacturing, manufacturing grids) and enterprise information technologies under the support of cloud computing, the Internet of Things (IoT), virtualisation and service-oriented technologies, and advanced computing technologies (Tao et al. 2011)	Reflects 1.1, does not reflect 1.2, 1.3, does not confirm to 2 and 3

important concept for smart manufacturing (Radziwon et al. 2014). Research on cloud manufacturing enterprise requirements and architecture should be conducted by referring to the concept of smart factory. Their similarities and differences should also be studied. Questions like 'can smart factories meet the requirements of cloud manufacturing enterprises?' should be answered.

- Maturity of cloud manufacturing systems and associated evaluation index. Implementation of cloud manufacturing is a long and gradual process. A cloud manufacturing system at different stages has different maturity levels. In the future, the maturity model of cloud manufacturing systems and associated evaluation indexes should be investigated and developed.
- Relationship between manufacturing cloud services and digital twins. Digital twin is a significant concept for smart manufacturing. A digital twin of a physical object is a virtual mapping of the object with real-time data transmission. Cloud services are encapsulated from manufacturing resources based on real-time data collection and virtualisation and servitisation. It is no doubt that manufacturing cloud services are closely related to digital twins. In the future, it is necessary to clarity their relationship to deepen people's understanding of cloud manufacturing services.

6.2. Industrial implementation

This section discusses issues and challenges regarding industrial implementation of cloud manufacturing.

6.2.1. Factors influencing implementation of cloud manufacturing

There are many factors that influence implementation of cloud manufacturing, which overall fall into the following four dimensions: scope, enterprise, industry, and technology:

- Scope. Cloud manufacturing can be implemented in different scopes, including within an enterprise, across different enterprises, in different regions, throughout a country or across different countries, and even around the globe, which can be deployed as a private cloud, community cloud, public cloud, or hybrid cloud. Generally, the difficulty for implementing cloud manufacturing varies with scopes. For example, the difficulty for implementing a private cloud is smaller than that of a community cloud, which in turn is smaller than that of a public cloud.
- Enterprise. The success of cloud manufacturing relies heavily on enterprises' adoption and participation. However, there are some basic requirements for enterprises to adopt and participate in cloud manufacturing in terms of enterprise information level and equipment digitisation level. Potential benefits, enterprise objectives and business requirements, competitive pressure, top management understanding and support, enterprise management and culture, enterprise size, employees' participation and cooperation, and implementation complexity are also important factors that affect the implementation of cloud manufacturing within an enterprise (Low, Chen, and Wu 2011).
- Industry. The manufacturing sector has many different industries. Different industries, discrete manufacturing or process manufacturing, have different characteristics and are at different stages of development. As a result, they have different degrees of requirements for cloud manufacturing, and the difficulties and complexities for implementing cloud manufacturing in them are also different. Generally speaking, implementing cloud manufacturing in industries that have strong requirements are relatively easy.
- Technology. Cloud manufacturing relies on many technologies for its implementation and operation, including IoT, cloud technology, service, knowledge, information and big data management technologies, security-related technologies, standardisation, etc. Some of the technologies (e.g. IoT, standardisation) are needed for building the cloud platform, some of the technologies are needed for managing and operating the cloud platform (e.g. service and knowledge management technologies), while some of them can impact enterprises' willingness to adopt cloud manufacturing. However, different technologies are at different stages of development. For example, technologies for virtualising hard manufacturing resources are still in its infancy. Prior to reaching the plateau of these underlying enabling technologies, it is almost impossible for cloud manufacturing to be fully implemented.

6.2.2. Problems faced by implementation of cloud manufacturing

Currently, cloud manufacturing industrial implementation is facing the following problems:

- The concept of cloud manufacturing is not sufficiently clear, including its intension, extension, boundary and capabilities. Currently, cloud manufacturing is generally described as a manufacturing paradigm that encompasses resources in the entire product lifecycle and is able to provide the manufacturing industry and enterprises involved with numerous advantages. This coarse-grained and macroscopic description of cloud manufacturing gives people the impression that the concept is too big and it is omnipotent. This actually confuses people regarding what cloud manufacturing is, what it can do and what it cannot do, and how to implement cloud manufacturing step by step. In order to make the concept clearer and more tangible, cloud manufacturing should be described in combination with concrete resources, enterprises, sectors, industries and regions, etc. Moreover, the concept of cloud manufacturing should be decomposed into smaller concept components and simplified in combination with concrete scenarios.
- The success of cloud manufacturing needs enterprises' widespread adoption and participation. In order to achieve this, enterprises need to be clear about three aspects: cloud manufacturing (including what cloud manufacturing is, what it can/cannot do, what benefits and advantages it is able to bring, why to adopt it instead of other manufacturing models or concepts), enterprise

(including what enterprises' requirements are and whether enterprises are well prepared for implementing cloud manufacturing) and implementation (including how to implement cloud manufacturing step by step, what associated risks are, what technologies are needed, and how much investment is needed). Currently, some enterprises are not quite familiar to the concept, and even know nothing about it, and it will take some time for enterprises to be familiar and accept cloud manufacturing (Zang, Liu, and Xu 2016). From the perspective of enterprise, many enterprises are not well prepared in many aspects for adopting, participating in and implementing cloud manufacturing, including enterprise information systems, architecture, management, etc. Much work needs to be done to make them meet the basic perquisites and requirements. Regarding implementation, enterprises lack specific ideas and routes as to how to implement cloud manufacturing. Some enterprises are even unclear about their requirements. Analysis of costs, benefits and risks for implementing or participating in cloud manufacturing should also be carried out.

- It has been pointed out in many previous works that numerous technologies are required for implementing cloud manufacturing. Li et al. (Li et al. 2011) have systematically summarised the key technologies for cloud manufacturing into eight categories, among which the most frequently mentioned technologies include IoT, cloud computing, semantic Web, service-oriented technologies, virtualisation, advanced high-performance computing technologies, and with advanced manufacturing models and information technologies. More recently, emerging technologies such as CPS, big data, AI, mobile Internet, etc., have also been incorporated into the technology system of cloud manufacturing. These technologies are proposed different perspectives, and they, to a great extent, have some overlaps with each other. In fact, overall they are the technologies for cloud manufacturing, but not all of them are needed for implementing a specific system. An important problem with these technologies is that the hierarchy of them has not been clarified. For example, which are core technologies, which are key technologies, and which are general enabling technologies (see Sections 2.6 and 5.1). So many technologies without any classification of their hierarchy impede the implementation of cloud manufacturing as enterprises don't know from where they should start and how to effectively integrate them, and ultimately they will be scared by the high complexity of implementing a cloud manufacturing system. Another problem is that each of the technologies necessary for cloud manufacturing is at a different stage of research and development. Objectively, it takes some time for them to reach their maturity. Prior to the maturity of the underpinning technologies, cloud manufacturing cannot be fully implemented. As a result, identifying their research and development stages and the degrees of their maturity is very important for development and implementation of cloud manufacturing.

6.2.3. Phases for implementing cloud manufacturing

This section presents four rough phases for implementation of cloud manufacturing, including preliminary implementation, relative complete implementation, complete implementation, and full implementation, from the perspectives of resource, platform, service and technology (Table 3).

7. Conclusion and discussions

In this paper, we have discussed key issues with cloud manufacturing and presented its future perspectives. The concept, operation model, service mode, service content, technology system, architecture, and essential characteristics of cloud manufacturing have been discussed. The discussion was carried out by comparing the issues with those in cloud computing, which helps clarify the issues of cloud manufacturing more clearly. The relationships between cloud manufacturing and some other manufacturing-related concepts such as cloud computing-based manufacturing, CPS, smart manufacturing, Industry 4.0 and Industrial Internet have also been discussed. Then, the requirements of cloud manufacturing definitions and principles for defining cloud manufacturing have been

Table 3. Phases for implementing public cloud manufacturing.

Phases	Implementation description
Phase1: preliminary implementation	• Resources: Several types (even a single type) of resources are aggregated into a cloud platform and the amount of the resources is also limited. • Platform: The platform possesses only simple functions and provides some simple applications. • Services: Only simple and limited resource and platform services are provided. • Technologies: Only several core technologies are employed for implementing a cloud manufacturing system.
Phase 2: relative complete implementation	• Resources: More types of manufacturing resources are registered to the cloud manufacturing, and the amount of resources is larger. • Platform: The platform can provide some complex functions and applications. • Services: More resource services and platform services are provided. • Technologies: More core technologies and some key technologies are employed for implementing a cloud manufacturing system.
Phase 3: complete implementation	• Resources: Almost all possible resources are aggregated into the cloud platform. • Platform: The platform possesses almost complete platform functions. • Services: Complete resource services and platform services are provided. • Technologies: Most of the core, key and enabling technologies are used to implement a cloud manufacturing system.
Phase 4: full implementation	• Resources: All possible resources are aggregated in a cloud platform. • Platform: The platform possesses all functions needed for an ideal cloud manufacturing system. • Services: All resource services and platform services necessary are provided. • Technologies: All core, key and general enabling technologies necessary are applied for implementing an ideal cloud manufacturing system.

presented and then an alternative definition was put forward based on analysis of 12 existing definitions according to the requirements and principles.

The future perspectives of cloud manufacturing were also analysed from the perspectives of both academic research and industrial implementation. For the former, the hierarchy of technologies of cloud manufacturing, the degree of involvement of enterprises in cloud manufacturing, requirements and architecture of enterprises in cloud manufacturing, maturity of cloud manufacturing systems, and relationships between digital twins and cloud manufacturing services were discussed. For the latter, factors that influence the implementation of cloud manufacturing, problems faced for implementing cloud manufacturing, and four different phases of implementation of cloud manufacturing and associated evaluation methods were discussed and presented.

Currently, smart manufacturing has been a hot research topic on a global basis and implementing smart manufacturing has been the common objective of many countries. In this context, there are great opportunities for the future development of cloud manufacturing. However, there are also numerous challenges in terms of concept, technology and industrial implementation of cloud manufacturing. At the same time, many new concepts and technologies have emerged, and there is a need to clarify the relationships with cloud manufacturing to facilitate understanding, development and implementation of cloud manufacturing. Furthermore, the lack of a standardised definition of cloud manufacturing also hampers its development. With the aim to discuss and clarify the issues, this paper conducted systematic discussion and analysis of the issues and presented future perspectives of cloud manufacturing, which is expected to deep people's understanding of cloud manufacturing and advance related research and implementation.

Nomenclature

AI	Artificial Intelligence
auto ID	Automatic IDentification
CAX	Computer-Aided Everything
CPS	Cyber-Physical Systems
CPSS	Cyber Physical Social Systems
CPPS	Cyber-Physical Production Systems
DaaS	Design-as-a-Service
DRC	Dynamic Resource Communities
EC2	Elastic Compute Cloud
ERP	Enterprise Resource Planning
FaaS	Fabrication-as-a-Service
GPS	Global Positioning System
IaaS	Infrastructure-as-a-Service
IIC	Industrial Internet Consortium
INaaS	Integration-as-a-Service
IoT	Interne of Things
IT	Information Technology
MaaS	Manufacturing-as-a-Service
MAaaS	Maintenance-as-a-Service
MES	Manufacturing Execution System
MGaaS	Management-as-a-Service
MIaaS	Manufacturing Infrastructure-as-a-Service
MPaaS	Manufacturing Platform-as-a-Service
MSaaS	Manufacturing Software-as-a-Service
OWL	Web Ontology Language
NIST	National Institute of Standards and Technology, USA
PaaS	Platform-as-a-Service
PRaaS	Production-as-a-Service
PSP	Distributed production Service Providers
QoS	Quality of Service
RFID	Radio Frequency IDentification
SaaS	Software-as-a-Service
SIaaS	Simulation-as-a-Service
SOA	Service-Oriented Architecture
SWRL	Semantic Web Rule Language
TaaS	Test-as-a-Service
WiFi	Wireless Fidelity
XaaS	Everything-as-a-Service

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