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ORIGINAL ARTICLE

Cloud manufacturing: challenges, recent advances, open research issues, and future trends

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Abstract
Cloud manufacturing (CMfg) is a new manufacturing paradigm over computer networks aiming at using distributed resources in the form of manufacturing capabilities, hardware, and software. Some modern technologies such as cloud computing, Internet of Things (IoT), service-oriented, and radio-frequency identification (RFID) play a key role in CMfg. In CMfg, all resources needed for manufacturing such as hardware, software, and manufacturing capabilities are virtualized; the services are provided by manufacturing resources. In this paper, the key characteristics, concepts, challenges, open issues, and future trends of cloud manufacturing are presented to direct the future researches. Accordingly, five directions of advances in CMfg are introduced and the articles in five categories are reviewed and analyzed: (1) studies focused on the architecture and platform design of CMfg; (2) studies concentrated on resource description and encapsulation; (3) studies focused on service selection and composition; (4) studies aimed at resource allocation and service scheduling; and (5) studies aimed at service searching and matching. The article also aims at providing a development diagram in the area of CMfg as a roadmap for future research opportunities and practice.

Keywords Cloud manufacturing · Resource virtualization · Semantic web · Service composition · Service matching · Scheduling

1 Introduction

Information technology is continuously growing so that it is the origin of many of core technologies such as cloud computing, Internet of Things, embedded systems, semantic web, service-oriented systems, virtualization, and radio-frequency identification (RFID). These core technologies together changed the shape of manufacturing from product oriented to service oriented and the new manufacturing paradigm is called cloud manufacturing [1]. Cloud computing service models, namely SaaS, PaaS, and IaaS, that offer computing resources as services in a convenient pay-as-use method could be applied in manufacturing so that all manufacturing resources are offered as a service [2]. To survive in the current globalization state, enterprises need a cooperative manufacturing system via the Internet. Multinational manufacturing factories usually have many resources that can share with each other. Additionally, they could offer their resources to other enterprises. In CMfg, manufacturing resources including machining tools, software such as computer-aided design/manufacturing/planning, and capacities such as design capability, management capability, test, and evaluation capability are virtualized and make a resource pool [3]. Customers could access the resources as services and manufacture their product. This means that customers in all around the world could use the distributed heterogeneous manufacturing resources for simple and complex tasks in supply chains. Some aspects of CMfg were studied by researches while many other aspects of it need deeper investigations. Our work tries to clarify these aspects. A number of researches with different details have already presented the latest findings and the state-of-the-art surveys of CMfg; some of them are mentioned here:

Wu et al. [4] focused on developing a strategic vision for the CMfg environment, considering the benefits of cloud

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computing to information technology. They mentioned the possible impact of CMfg on three key sectors including engineering design and manufacturing, as well as marketing and service. He et al. [5] presented a state-of-the-art survey of CMfg. Their work suffered from a lack of evaluation of the provided solutions for different aspects of CMfg.

A comprehensive literature review on CMfg was presented by Adamson et al. [6]. In the paper, challenges in modern manufacturing were investigated to understand the possible impacts of CMfg. Tao et al. [7] provided an overview of manufacturing service management (MSM) in CMfg. The authors focused on MSM, while other aspects of CMfg were not investigated enough. By a literature review, Tarchinskaya et al. [8] concluded that cloud computing as a core technology could help to change the way of enterprises operation in the manufacturing industry. The paper suffered from a lack of investigating CMfg solutions and various aspects of it.

To help future researchers in the field of CMfg in providing novel solutions and mechanisms, we surveyed the literature and analyzed the state-of-the-art solutions. Therefore, the purpose of this paper is to survey the current solutions for CMfg, describe their properties, and clarify their pros and cons. The main goals of this paper are as follows:

- The unique contribution of this paper is providing a development diagram for cloud manufacturing aiming at presenting a roadmap for open issues and future researches. We showed the diagram in Fig. 14. As shown in the figure, CMfg had an impact on manufacturing, industry, and technology implementation, and is facing general issues.
- Analyzing the recent articles in the field of CMfg and clarifying recent advances on it
- Providing a classification of various aspects of CMfg and reviewing the articles of each class
- Outlining the key areas where new researches can be done to promote the CMfg future researches

The rest of the paper is organized as follows. Section 2 provides a literature review of the concepts, characteristics, and challenges in CMfg. Section 3 provides a relatively comprehensive review of literature in CMfg as well as a new classification. Section 4 provides a discussion of the mentioned techniques and some useful statistics. Open issues are outlined in Section 5. Finally, in Section 6, we conclude our survey and provide future trends.

2 CMfg: concepts, characteristics, challenges, CMfg vs cloud computing

The term, CMfg, was first used by Li, et al. [9] in 2010, defined to be a service-oriented, knowledge-based smart manufacturing system with high efficiency and low energy consumption. CMfg is a manufacturing paradigm over networks that connects distributed resources and capabilities, by using the new generation of information technologies such as big data, IoT, cloud computing, and the Internet. Alternatively, CMfg is a service-oriented technology for automating the process of manufacturing through a pool of configurable virtualized resources with the minimum intervention of service providers. As a promising way of creating a basis for agility, service-oriented technologies have gained attention in the past few years, so that the company can deliver a flexible business process for satisfying the customers. Resources in CMfg consist of manufacturing capabilities, hardware resources, and software resources. In CMfg, services are provided by resources and are managed in a central manner. Cloud users can request services ranging from product design, manufacturing, to testing, management, logistic, maintenance, and all other steps of a product life cycle [1–3, 10]. Technologies such as IoT, cloud, Cyber-Physical System (CPS), RFID, and big data [11] are cutting-edge ICT technologies which play an important role in CMfg. CPSs are integrations of computation and physical processes [12].

2.1 An overview of the concepts of CMfg

There are some concepts in cloud manufacturing that need attention:

- *Service*: a service is a mechanism that can provide one or more functions, which is possible to use inconsistent with provider-defined rules and constraints through an interface. Samples of CMfg services are design services, simulation services, production services, testing services, management services, and maintenance services. From a technical view, cloud services could be divided into two classes: OffCloud services, which means that some manufacturing tasks should be operated by human factors out of the cloud manufacturing environment, such as activities on machine tools and material logistics; OnCloud services, which is in full control of a cloud platform [13, 14].
- *Resource* is an entity that performs a function or activity in the process of the product lifecycle. Distributed resources that are virtualized as services in CMfg are categorized into three class: manufacturing capabilities, hardware resources, and software resources. Manufacturing capabilities include production capabilities, management capabilities, testing capabilities, experimentation, and maintenance but not limited to these [15]. Hardware resources include computer servers, machine tools, equipment, raw materials, and software resources include “know-hows,” analysis tools, and simulation tools. The types of manufacturing resources are summarized in Fig. 1.

- *Resource virtualization* is the process of mapping from real manufacturing resources into logical ones in order to improve agility, enhance flexibility, and reduce cost. In the virtualization process, where the manufacturing resources are encapsulated into services, three different mapping models are used: one-to-many, one-to-one, and many-to-one. [2, 3].
- *Capability Servitization* is an encapsulation process from an abstract description of a manufacturing capability to a formalized cloud service according to a specification [1, 3].
- *Cloud Manufacturing Platform* provides integrated IT-based tools and the infrastructure for both suppliers and demanders. A pool of CMfg resources is under the management of this entity over a computer network. Cloud manufacturing platform plays an important role in matching supply and demand, dynamic construction of a virtual system connected with resources, services and users, service execution and efficient collaboration, comprehensive rating, and pay-as-use payment [3, 14].

- *Provider, operator, and customer* are three actors in CMfg. The provider is an entity that provides manufacturing capabilities and resources as service and acquires business income and reputation. The operator is an entity that manages the CMfg platform. Customer refers to an entity that demands an application for the process of the product lifecycle and gets competitive services [2, 14]. The interactions between CMfg actors are summarized in Fig. 2.

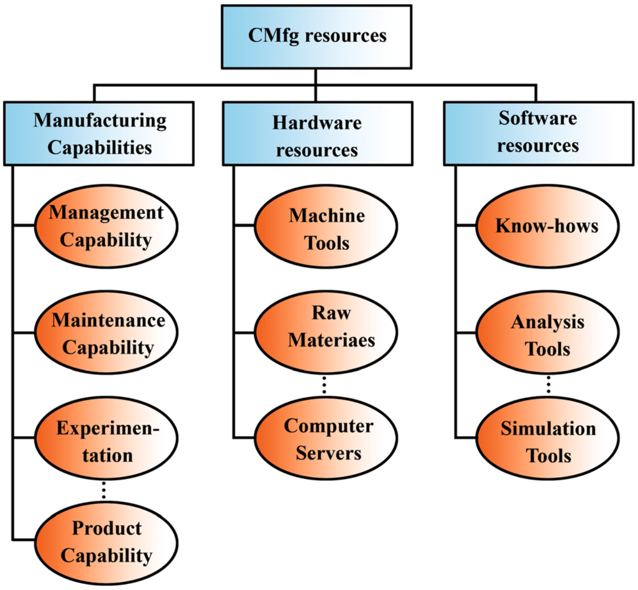


Fig. 1 Types of resources in CMfg [2]

- *Virtual service pool.* In CMfg, all resources are encapsulated and stored in a pool of manufacturing resources that are configurable and can be rapidly allocated and released on-demand with minimum service provider intervention and management effort [3].

2.2 Characteristics of CMfg

Compared with the existing manufacturing models, CMfg has typical characteristics mentioned in [13, 16, 17] and we summarize them here:

- *Service-oriented and requirement-oriented*. While the most manufacturing models are resource-oriented or order-oriented, CMfg is a service-oriented and requirement-oriented manufacturing model. In CMfg, the capabilities and manufacturing resources, distributed in different geographical location, are virtualized and encapsulated into manufacturing cloud services. Its goal is to sharing of capabilities and manufacturing resources, and to enable manufacturing resources and capabilities to be used according to requirements.
- *Dynamic with uncertainty*. Resources and services in Cloud manufacturing are diverse and dynamic. Therefore, the solutions for handling the manufacturing tasks are also dynamic. Authors of [17] mentioned 32 uncertainty factors and categorized them into three groups.
- *Intelligent perception of manufacturing resources*. In CMfg, all types of manufacturing resources are encapsulated in the form of services. Dynamic states of hard manufacturing resources in CMfg can be perceptible with cameras, intelligent sensors, barcodes, and RFID; all kinds of networks such as the Internet, 3G/4G, satellite networks, and sensor networks can be used to transfer and handle the collected data.
- *Knowledge-based manufacturing*. The success of CMfg depends to a great extent on the knowledge base. All types of manufacturing services along with the corresponding knowledge are stored in the CMfg system. Along with the evolution of CMfg, the knowledge base is continually expanding in the cloud.
- *Physically distributed and logically centralized*. The manufacturing resources and capabilities in CMfg are located in different geographical places and are controlled by different persons or organizations. However, they are all virtualized and encapsulated into a CMfg system, which is managed, controlled, and used centrally in logic.
- *Initiative*. In a CMfg system, both supply (service) and demand (task) are active, so that the process of finding

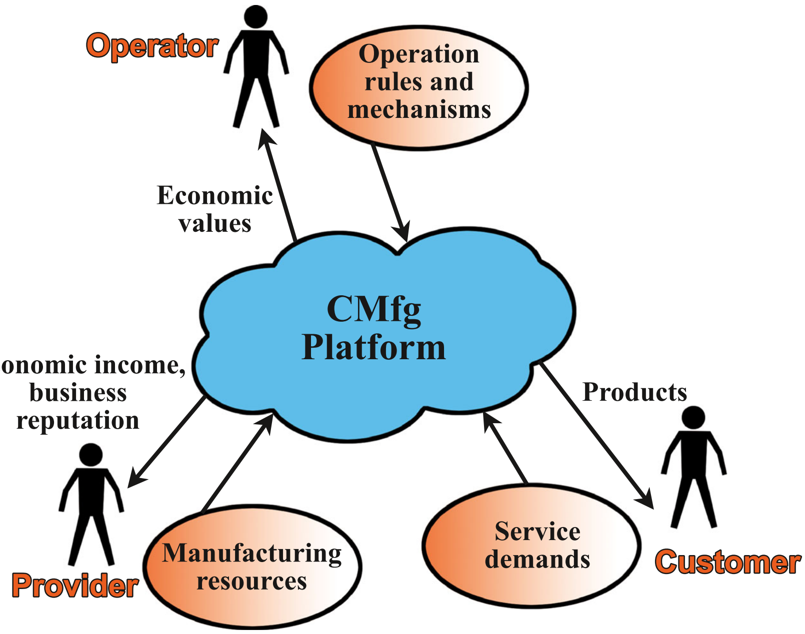


Fig. 2 Actors and their interactions in CMfg [14, 15]

and matching each other is automatic based on the semantic similarity knowledge.

2.3 Cloud computing vs. CMfg

Cloud manufacturing is enabled by a number of technologies: (1) the traditional manufacturing process, (2) cloud computing, (3) IoT, (4) virtualization, (5), service-oriented technologies, and (6) advanced computing technologies [13, 16]. Among them, CMfg has similarities and differences with cloud computing. Cloud manufacturing was proposed after cloud computing that is a core technology for CMfg. From a service providing viewpoint, cloud computing and CMfg are different. Cloud computing provides three service models, including Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS) [2]. Resource in cloud computing are computing resources. In CMfg, in addition to computation resources, required manufacturing capabilities and resources are encapsulated and involved in the lifecycle of manufacturing aimed at providing the user with different service models based on IaaS, PaaS, and SaaS. They include the following models: Experimentation as a Service (EaaS), Design as a Service (DaaS), Management as a Service (MaaS), Manufacturing as a service (MFaaS), Maintenance as a Service (MAaaS), Integration as a Service (INTaaS), and Simulation as a Service (SIMaaS). The differences and relationships between cloud computing and CMfg are shown in Fig. 3 [16]. Cloud computing services include computational software resources and capability services, while in CMfg, in addition to these services, diverse manufacturing capabilities and resources are provided as services. The specific services of CMfg make enterprise systems more powerful and a higher-level extension of traditional services [18].

2.4 Challenges in CMfg

Cloud manufacturing is a promising new service-oriented manufacturing paradigm that can transform the traditional industry. However, our literature review revealed several challenges in cloud manufacturing paradigm. A number of studies [12, 19–23] mentioned the challenges summarized below:

- *Security:* it is one of the major issues, which hamper the growth of cloud manufacturing industry. The researchers are providing a security framework for cloud manufacturing.
- *Demand uncertainty:* Customer demands are not predictable, and demand uncertainty influences the effectiveness of production planning. For more than three decades, researchers have been working on finding better methods for planning the production activities under the mentioned uncertainty conditions.
- *Variability in manufacturing systems:* Various types of manufacturing systems formulate the production planning in different methods.
- *Unwillingness to adopt CMfg technologies:* social acceptance awareness of cloud manufacturing technology is inadequate.
- *Legal issues*: In cloud manufacturing, stakeholders should transfer corresponding data through wireless networks or uploading data onto the Web that may result in data disclosure.
- *Knowledge and trust management*: Cooperation of two factories to manufacture a product required the scalability

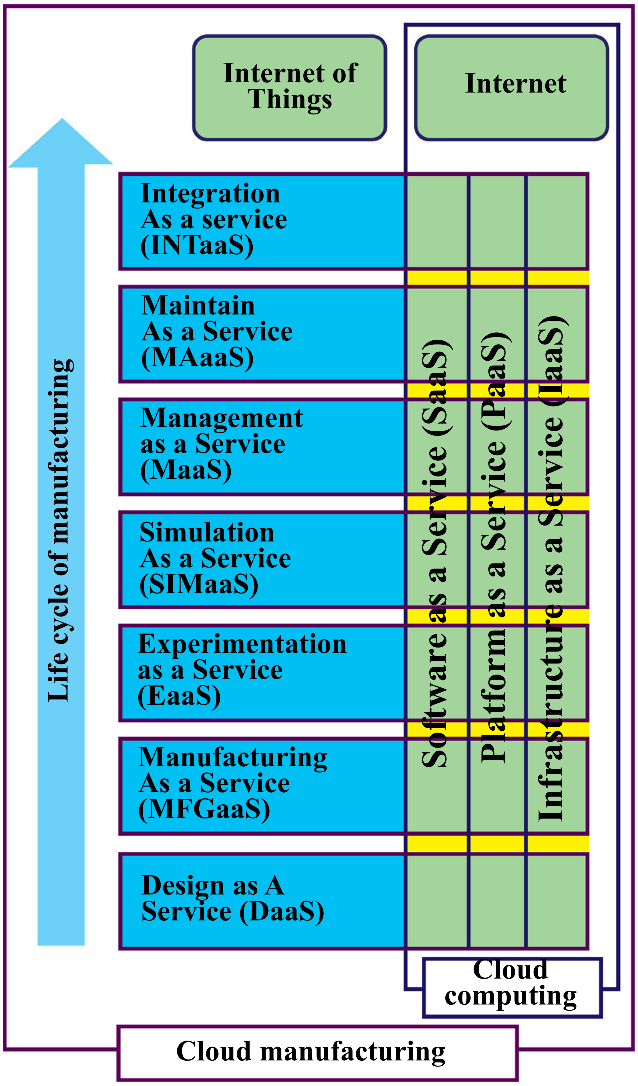


Fig. 3 Relationships between CMfg and cloud computing [16]

and interoperability of both factories and their mutual trust [20].

- In CMfg, the demands from a customer or one factory are converted to a product, able to another factory for manufacturing. This process needs the scalability and interoperability of both stakeholder and relies on mutual trust.
- *Heterogeneous manufacturing virtualization and integration:* In CMfg establishment, different sensors are used for tracing raw materials, operators, and pallets.
- *Deployment cost*: The costs of ubiquitously deploying manufacturing resources could be huge.
- *Others*: such as (1) identification, (2) localization, (3) status knowledge, (4) updating the smart manufacturing system, (5) support for different queries, (6) integration of heterogeneous information, and (7) real-time characterized reaction.

3 Literature review on CMfg and classifying the studies

In this section, we survey the literature on CMfg. For this purpose, we searched famous databases such as ScienceDirect, ACM, IEEE, and Google Scholar and found a significant number of articles published in journals and presented at conferences. After filtering of them, we selected 94 articles. Some of them were review papers; some of them paid attention to the general characteristics and concepts of CMfg. We classified the other papers into five categories: (1) studies focused on designing the architecture and platform of CMfg (DAP), (2) studies concentrated on resource description and encapsulation (RDE), (3) studies focused on service selection and composition (SSC), (4) studies aimed at resource allocation and service scheduling (RASS), and (5) studies aimed at service searching and matching (SSM). We studied a number of articles in each category and analyzed them.

3.1 Studies focused on the architecture and platform design of CMfg

Our literature review showed that a significant number of authors paid attention to the CMfg architecture that some of them are investigated in this section. A cloud manufacturing system framework with four layers was presented by Xu [2]. The author considered four layers in the proposed framework: application layer, global service layer, virtual service layer, and manufacturing resource layer. The author discussed that CMfg paradigm will provide effective solutions to the manufacturing industry that is becoming increasingly distributed and globalized.

Tao et al. [16] proposed a detailed architecture of a CMfg system with ten layers. They found that the proposed model enhanced resource utilization while reducing the resource and energy consumption. Qu et al. [24] proposed a framework for smart cloud manufacturing (S-CM) based on the IoT with three layers. They found that the integration of IoT and CMfg in order to use their respective advantages provides a generic way for mixed implementation of IoT and CMfg.

Wu et al. [25] proposed an architecture for cloud-based design and manufacturing (CBDM) that is a service-oriented model for product development. The authors discussed that design and manufacturing based on the cloud can be considered as a modern paradigm that will change the future of manufacturing process. Wang et al. [26] presented their study on the concept and the characteristics of the CMfg and provided a service-oriented system. They found that cloud technologies could change the manufacturing industry and businesses.

Liu et al. [27] presented a new CMfg architecture for cloud-based machining complex parts. The authors developed a prototype CMfg system to demonstrate how the proposed

Table 1 An overview of studies focused on the architecture of CMfg

Authors and date	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Qu, et al. [24], 2015	International Journal of Advanced Manufacturing Technology	Using IoT for the problem of dynamic production logistics synchronization (PLS)	• Integration of CMfg and IoT • Dealing the dynamics occurring in production logistics processes	• Not considering many practical rules and constraints in the PL process • Providing a qualitative solution and no quantitative with the mathematic formalization	• Real implementation
Wu et al. [25], 2015	Journal of Computer-Aided Design	Introducing Cloud-based design and manufacturing as a new paradigm	• Comparing processes of traditional design and cloud-based design • Providing a new layering architecture for CMfg	• No specified the suitable design and manufacturing services • No specified impacts of future technologies on CBMD • No specified strategic models for providers	• Providing an idealized scenario Implementation of a scenario
Liu et al. [27], 2015	Journal of Manufacturing Science and Engineering	Using Standardized Machining Task Description Strategies (SMTDS)	• Protecting proprietary machining know-rows • Guaranteeing the service quality • Providing a new CMfg architecture	• Lack of intelligent algorithms for service matching to improve the performance of proposed architectures • Enrichment of SMTDS is necessary for more complex part types	• Developing a prototype system • Case study
Yang, et al. [28], 2015	International Journal of Advanced Manufacturing Technology	Integrating multiple CMfg	• Using aggregated manufacturing resource and capabilities • Users access to a wide range of services	• No efficient collaboration algorithms provided • Not considering the issues such as security and privacy • To deal with uncertainties it needs event-driven service selection	• Using a case study • Implementation in conglomerate
Wang, et al. [26], 2013	In Cloud Manufacturing Conference	Providing an Interoperable Cloud-Based Manufacturing System (ICMS)	• Investigating cloud computing with a manufacturing view • Providing a market-oriented cloud architecture • Focusing on standardization	• The integration and collaboration issues between multiple autonomous heterogeneous CMfg are not addressed • No mention to future works	• Case study • Using the Java Agent program
Xu, et al. [2], 2012	Journal of Robotics and Computer Integrated Manufacturing	Introducing cloud computing as a core technology for CMfg	• Providing an architecture for CMfg •Present a relation between cloud computing and CMfg	• Components of each layer of CMfg architecture not provided • CMfg needs another module to manage virtualized resources	• No simulation or implementation
Tao, et al. [16], 2011	Journal of Engineering Manufacture	Introducing the concept, architecture, and enabling technologies of CMfg	• Comparing cloud computing and CMfg. • A detailed architecture for CMfg	• No description of modules (components) of architecture	•No simulation or implementation

architecture works for finding machining services for complex parts. Yang et al. [28] proposed a hybrid framework for integrating multiple CMfg. To demonstrate the rationality and feasibility of the proposed hybrid framework, the authors provided a case study.

The investigated articles in the DAP category are analyzed in Table 1. In the table, we considered columns for authors and year, journal/conference, main idea, pros, and cons, as well as the evaluation techniques of the articles.

3.2 Studies concentrated on resource description and encapsulation (RDE)

In this subsection, we investigate the studies focused on two topics: perception and description of resource manufacturing and capability servitization, which refers to the transformation from abstract capabilities to formalized cloud manufacturing services. Based on a literature review, we can draw a high-level process of resource perception, description, and servitization as in Fig. 4. The techniques of IoT are being used to perceive manufacturing cells, enabling intelligent identification, monitoring, tracking, locating, and management. The common adopted techniques include RFID and sensor systems, transforming those passive machines into proactive agents. For example, temperature sensors and pressure sensors can be used to perceive the real-time state of chemical devices, and once a dangerous signal appears, the remote controller in a cloud can throw an alarm in time. Sensor data will be collected and preprocessed, then delivered to a cloud platform via the Internet. As known, RFID has been applied in tracing materials in logistics. The other type of hard resource, IT hardware, as well as soft resource, can be connected to a cloud platform over the Internet by using traditional techniques. Hence, a cloud platform may keep watch on them through their exposed interfaces [1, 3].

Zhang et al. [29] presented a services encapsulation and virtualization access model for manufacturing machines. The model upgrades the traditional machine to satisfy the new requirements of cloud manufacturing. The authors used a case study to illustrate the implementation of the proposed service model. Luo et al. [30] established a method for describing and modeling the multidimensional information in a CMfg system. The effectiveness of the proposed method was validated by a case study.

Tao et al. [31] found that realization of the intelligent perception and access to manufacturing resources and capabilities was one of the bottlenecks in CMfg implementation. Xu et al. [32] described the dynamic modeling of manufacturing equipment capability using condition information. They implemented the system and found that the proposed framework could handle the dynamic nature of CMfg environment.

Yu et al. [33] modeled the manufacturing equipment capability dynamically using the Web Ontology Language (OWL. They validated the effectiveness and operability of the proposed method by a case study. Wang et al. [34] proposed a four-layered Additive Manufacturing (AM) resource virtualization framework. Their work simplifies the actual configuration of the cloud platform and decreases the technical barriers and cost, promoting the practical process of 3D printing technology. To develop a protocol and a service

Fig. 4 Resource reception in CMfg [3]

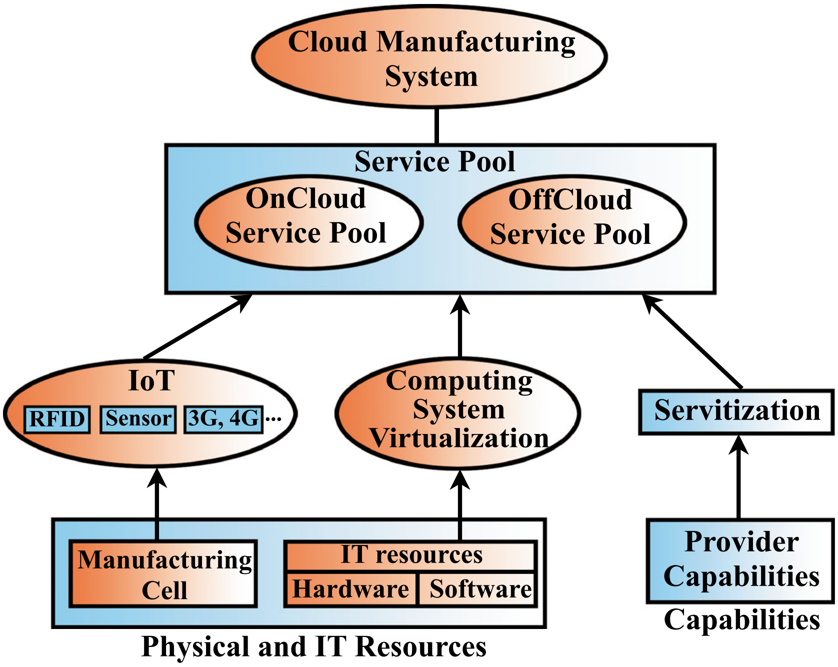


Table 2 An overview of studies focused on resource and capability description

Authors	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Wang et al. [34], 2016	In Cloud Computing and Big Data Analysis, 2016 International Conference	Abstraction of hardware and software resources, constructing manufacturing resource pools	• System flexibility due to the decentralized resource management • Simplifying the configuration of cloud platform • Scalable, flexible, efficient	• No systematic test of the AMCP resource access, operation management, and third-party app integration	• Two case studies • Evaluate by implementation
Zhang et al. [29], 2017	Journal of Intelligent Manufacturing	Using IoT and cloud computing for service encapsulation	• Provides a comprehensive information in a CMfg environment • Providing an optimal configuration and scheduling of resources, Scalable	• It is not obvious how to use real-time information to support prediction and scheduling	• Case study • A prototype system implementation
Xu et al. [32], 2015	Journal of Manufacturing Science and Engineering	Knowledge description of manufacturing capability with static and dynamic information	• Building ontologies of manufacturing equipment • Mapping real-time condition data • Dynamic monitoring of equipment • Optimal utilization of equipment • Real-time update of knowledge structure	• No implementation at the widespread level	• Using a case study • Developing a prototype system
Tao et al. [31], 2014	IEEE Transaction on Industrial Informatics	Using IoT for manufacturing resource intelligent perception and access	• A solution for resource description • A good start point for future perception	• Is a primarily attempt • No specified protocol, safety, and security, reliability and management technology for the IoT	• Developing a prototype application system
Yu et al. [33], 2014	In ASME 2014 International Manufacturing Science and Engineering Conference	Information modeling of manufacturing capability in cloud manufacturing	• Dynamic description of manufacturing equipment capability • QoS can dynamically evolve in terms of abstract knowledge convenient discovering, sharing and reuse the capability	• Focused on static attributes of manufacturing service capability, while a practical	• Developing a prototype System • Conducting a set of experiments
Lu et al. [35], 2014	Journal of Manufacturing Research	Developing a resource description protocol for CMfg	• Reduction in system development effort • Reducing maintenance costs • Facilitating complex decision-making • Facilitating resource retrieval and service delivery	• The approach is less effective in real cases • Not contain the specification of costs, project timeframe and logistics	• Verified the approach by two examples • Implementing ontology
Luo et al. [30], 2013	Journal of Advanced Factoring Technology	Manufacturing capability description in CMfg	• Comprehensive and systematic • Solving aormalization of fuzzy concepts • Supporting demand of different manufacturing capability services • Improving resource utilization	• No discussion of the logical shift between fuzzy description logic and dynamic description logic	• Case study • Construct a multidimensional model

description language for describing the manufacturing resources, Lu et al. [35] established an ontology-based model. The model facilitates complex decision-making processes in a cloud manufacturing environment.

The investigated articles in the RDE category are analyzed in Table 2. In the table, we considered columns for authors and date, journal/conference, main idea, pros, and cons, as well as the evaluation techniques of the articles.

3.3 Studies focused on service selection and composition (SSC)

In this subsection, we investigate a number of recent articles in the field of service selection and composition in CMfg. Some authors refer to service selection and composition as a service configuration. Service composition in CMfg is a key technology to promote the development of manufacturing. Distributed and heterogeneous CMfg services are integrated into a CMfg platform to make a pool of virtualized manufacturing services. To complete the manufacturing task in CMfg, it is essential to have a group of services that work together. Therefore, all possible composite cloud manufacturing services should be constructed under constraints of the task requirements with respect to the quality of service constraints. Then, an optimal composite cloud manufacturing services are selected from all the candidates to execute the CMfg task and finally return the results [36, 37]. Figure 5 shows the process of service composition in cloud manufacturing.

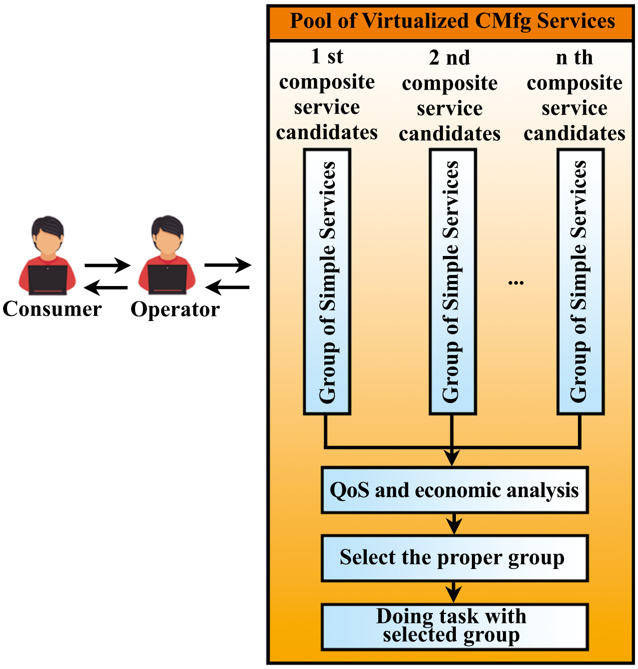


Fig. 5 Process of service composition in CMfg

Therefore, the service composition process in general consists of two phases: (1) capability assessment, which is to find feasible resources for a given task, based on the characteristics of the task and the capability of each unique resource, and (2) service recommendation, where the economic analysis and sustainability analysis are carried out, after which an optimal set of manufacturing resources is recommended [38]. Here are a number of studies concentrated on service selection and composition.

Lartigau et al. [39] provided an efficient method for service composition in CMfg by considering Quality of Service (QoS), manufacturing time over availability and geo-perspective transportation. They found that the proposed mechanism was time-consuming, but had high efficiency, scalability, and optimization. Lu et al. [38] proposed a systematic framework for capability assessment and service recommendation in a CMfg environment. Their integrated service composition module successfully connects sales engineers from multiple workshops.

Liu et al. [40] proposed an approach to improve the overall QoS and increase the success rate. Zhou et al. [41] proposed a multi-objective hybrid artificial bee colony algorithm for service composition and optimal selection, taking into account the QoS and energy consumption in CMfg. The proposed algorithm achieved a good balance between computational complexity and solution quality.

Zheng et al. [42] proposed an integrated resource service selection approach for providing optimal manufacturing services to customers. Simulation results showed that the performance of their proposed approach is high. Zhang et al. [43] proposed a model to address the manufacturing service configuration problem in a cloud manufacturing system. A case study demonstrated that the service configuration results achieved in the analytical target cascading method were the same as the results of the central optimization method.

The problem of the large-scale service composition in CMfg was addressed by Zhou et al. [44] through a multi-population parallel self-adaptive differential artificial bee colony algorithm. Li et al. [45] proposed a two steps novel approach called service clustering network-based service composition.

Liu et al. [46] proposed a model for multitask-oriented service composition and scheduling in CMfg, in which key features of cloud manufacturing such as dynamic change of service availability, including transportation were considered. Zhou et al. [47] proposed a hybrid-based optimization algorithm to address the problem of optimal service composition. The authors used the teaching-learning method and considered the correlation among the services.

Huang et al. [48] proposed a new optimal algorithm named CCOA to address the problem of composition optimal-selection in CMfg. By simulation, they found that the efficiency of the proposed model was high while the time consumption was low. Chen et al. [49] proposed a novel optimization method named QWSC to handle the problem of service composition. This multi-objective method considers the QoS. Kumar et al. [50] proposed a model to select an appropriate cloud service provider in a fuzzy environment, considering some ranking parameters.

Liu et al. [36] proposed an approach for multipath CMfg services composition method with QoS constraint hierarchical (CH) model. Zhang et al. [51] proposed a novel and efficient method that employed the skyline operator and the Improved Flower Pollination Algorithm (IFPA) to solve the problem of QoS-based manufacturing service selection and composition. Liu at al. [52] proposed a multi-task oriented model for service composition and optimization in CMfg environments.

A novel case-library method for designing an efficient algorithm to tackle the problem of service composition and optimal selection in big data was proposed by Xiang et al. [53]. The authors compared their method to the existing optimization algorithms and obtained a better optimization result in large-scale CMfg. Sheghir et al. [54] addressed the QoS-aware cloud-service composition problem and proposed a hybrid genetic algorithm (HGA) combining genetic algorithm and fruit fly optimization algorithm to solve it. Karimi et al. [55] presented an efficient method for service composition in cloud computing using a combination of a genetic algorithm and data mining techniques. Tao et al. [18] presented a novel parallel intelligent algorithm named full connection based parallel adaptive chaos optimization with reflex migration (FC-PACO-RM) for solving service composition problem.

The investigated articles in the SSC category are analyzed in Table 3. In the table, we considered columns for authors and date, journal/conference, main idea, pros, and cons, as well as the evaluation techniques of the articles.

3.4 Studies aimed at resource allocation and service scheduling (RASS)

In a service-oriented paradigm for cloud manufacturing, multiple users are allowed to request services at the same time. The users submit their required tasks to a CMfg platform. Multiple manufacturing tasks can be performed in parallel in a CMfg environment due to the centralized operation and management of manufacturing virtualized services. Therefore, in CMfg, the optimal scheduling of manufacturing tasks is an important issue to achieve better performance of a cloud manufacturing platform. Allocation of resources in cloud manufacturing is one of the key points of cloud manufacturing technology that needs efficient scheduling algorithms. Based on a literature review, we showed a high-level model of multi-task scheduling in CMfg, which is illustrated in Fig. 6 [56, 57].

Liu et al. [56] presented a CMfg multi-task scheduling model that incorporates task workload modeling. The authors carried out various workload-based task-scheduling methods and investigated the system performance parameters. Wu et al. [58] presented a service allocation optimization mathematical model to tackle the task scheduling problem.

Zhou et al. [59] analyzed the dynamic task scheduling process in CMfg and then proposed a method of dynamic scheduling based on real-time simulation. Then, they proposed a framework for this method with three layers. Li et al. [60] proposed a CMfg scheduling model to exploit the distributed resources. They investigated four methods for robot deployment and considered three optimization objectives, including load balancing between robots, total cost minimization, and total processing time minimization.

Cao et al. [61] proposed a service selection and scheduling model for CMfg environments. The proposed model considered four criteria, i.e., time (including logistic time), quality, cost (including logistic cost), and service (TQCS). Cheng et al. [62] addressed a scheduling problem in CMfg where enterprises share their resources with each other. They applied a genetic algorithm based on the real number matrix encoding and designed crossover and mutation operation rules for the real number matrix.

Wang et al. [57] proposed a resource-scheduling model containing four indicators of cost, time, quality and risk with their own mathematical expressions. Laili et al. [63] presented a new improved energy adaptive immune genetic algorithm for satisfying the high efficiency and fast response requirements of scheduling services in CMfg.

Jian et al. [64] proposed an optimization model in order to effectively save time and reduce the cost of workshop production. They applied an improved cooperative particle swarm optimization algorithm with fast convergence and strong ability to avoid local optimization to solve task-scheduling issues. Barenji et al. [65] proposed a scheduling system for manufacturing flow lines (MFLs). They developed a dynamic and multi-agent system. Cui et al. [66] proposed a new algorithm named K-means-PSO (Particle Swarm Optimization) combined by K-means clustering and PSO algorithm to solve the scheduling problem in CMfg. Thekinen et al. [67] considered the problem of resource allocation in CMfg as a bisection matching problem and analyzed four different bisection matching techniques based parameters such as monotonicity, stability, and consistency. They concluded that each of the four techniques is suitable for a specific scenario.

Lartigua et al. [68] provided an optimized methodology for task scheduling. They focused the scheduling constraints, challenges, and the environmental data for the scheduling process. Akbaripour et al. [69] proposed four multi-objective Mixed Integer Programming (MIP) models for solving the service selection and scheduling with a sequential, parallel, loop, and selective subtasks' composition structures, respectively.

Table 3 An overview of studies focused on service selection and composition

Authors and Date	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Lu et al. [38], 2017	Journal of manufacturing systems	• Developing an environment for fast resource allocation	• High accurate • Real-time querying of production capacity • Providing accurate capability information • Real-time resource availability information • Flexible in managing resources	• Is a time-consuming process • Requiring professionals with semantic-web knowledge	• Using a case study to validate the performance of the approach • Implementation for a high-performance mechanical seals provider
Zhou et al. [41], 2017	Journal of Production Research	• Using ABC and cuckoo search algorithm for service composition and optimal selection	• Sufficient information sharing • High optimization • High efficiency • High scalability • Better performance	• No address multi-task scheduling and multitask-oriented service composition • Time-consuming • No tackle problems with more than three objectives	• Doing two experiments • The experimental environment is MATLAB R2013b
Zhang et al. [43], 2017	Journal of Cleaner Production	• Using the analytical target cascading model for service configuration	• Favorable time, cost, energy consumption • Low optimization time in a parallel environment • Achieving an autonomous decision right of the provider • Improved efficiency in parallel	• High optimization time in single PC (lower performance) • Complexity is proportion to the number of nodes	• A case study for implementing the model by considering five different service providers
Zhou et al. [44], 2017	Journal of Applied Soft Computing	• Optimal service selection using a multi-population parallel self- adaptive ABC algorithm	• High fitness value • High solution stability • Lower deviations of QoS fitness values • High performance	• Considering single objective service composition	• Experiments using PC with an Intel Core i54570 (3.2 GHz
Li et al. [45], 2017	Journal of Computer Integrated Manufacturing	• Using a clustered approach for service composition	• Fulfilling Mfg tasks without task decomposition • High efficiency • Decreasing the difficulty of service composition	• The proposed method not verified with real enterprise service • No composition optimization algorithm provided • No construction of the network itself	• Simulation Experiments using Pajek software • Case Study Implementation
Zhou et al. [47], 2017	Journal of Advanced Manufacturing Technology	• Combining ABC optimization and cuckoo search for service composition in CMfg	• High performance • High computation for searching correlation • High stability and convergence	• Considered correlation is limited to business correlation • Not considering multi-objective optimization • No scalability • High time	• A case study using MATLAB R2013b for 64-bit Windows 7 operating system, on a 2.5-GHz PC with 4 GB RAM.
Kumar et al. [50], 2017	The Journal of Supercomputing	• Selection the most appropriate cloud service among the set of alternatives	• Considering nonfunctional QoS requirements • Efficient, Scalable, Reliable	• No real implementation	• A case study in a real problem of cloud service selection and sensitivity analysis

Table 3 (continued)

Authors and Date	Journal/Conference	Main Idea	Pros	Cons	Evaluation
			• Better performance than compared algorithms		
Liu et al. [40], 2017	Journal of Advanced Manufacturing Technology	• Release the assumption of one-to-one mapping • The mapping between elementary services and subtasks	• More success rate • Better QoS • High optimization • High performance	• Tasks with Severe QoS constraints cannot be solved • In a real manufacturing business, QoS of each subtask is not absolutely	• Simulation experiments using MATLAB R2011b on a dual-core 2.40 GHz PC with 4 GB RAM under Windows 7.
Zheng et al. [42], 2016	Journal of Advanced Manufacturing	• Obtaining optimal manufacturing service using PSO algorithm	• High fitness value • Optimized composition • High performance • Favorable efficiency	• Lack of semantic QoS representation • No, optimize in the big data environment	• Developing CMfg prototype by using My Eclipse and MySQL for mold industry
Liu et al. [46], 2016	Journal of Computing and Information Science in Engineering	• Deal with multiple tasks at the same time in CMfg	• Schedule heterogeneous tasks efficiently • High service utilization • Decreasing average pass rate	• Not considering task constraints, task priority, and continuous task arrival • Increasing average completion time • Assuming the existence of service composition candidates	• Simulation experiments • No tools mentioned
Chen et al. [49], 2016	Journal of Computers and Industrial Engineering	• Using a multi-objective optimization method for service composition in CMfg	• Suitable for large-scale problem • Flexible, Efficient • Providing enhanced information for decision-making • Providing a multi-objective solution	• Using a well-defined composition schema	• Simulation using MATLAB Matlab7.1
Liu et al. [36], 2017	Journal of intelligent system	• Providing a multi-path approach for CMfg service composition	• Considering QoS constraint • Satisfy the needs of service application • Effective • High performance	• No real implementation	• Programming in C++ and running on Pentium(R) 4, 2.66 GHz; Memory: 512 M; OS: Windows XP, 2002.
Zhang et al. [51], 2016	Journal of Mathematical Problems in Engineering	• Providing flower pollination algorithm for service selection and composition	• Efficient • Considering QoS constraints • High fitness values • High performance	• It is a single objective • No real implementation	• Programming in C# for a case study, on a PC with Windows 7. Comparing with other algorithms
Xiang et al. [53], 2016	Journal of Advanced Manufacturing Technology	• Providing a novel case-library method for service composition and selection in CMfg	• Scalability • High efficiency • High accurate • High optimization	• Not considering Big Data in each phase of service composition and selection • No real implementation	• Developing a prototype system for a magnetic bearing manufacturing
Seghir et al. [54], 2018	Journal of Intelligent Manufacturing	• Using a hybrid algorithm for QoS-aware service composition in a cloud	• High feasible rate • Low computation time • High optimization	• Mono-objective • Not considering interdependencies and correlations among cloud services	• Using MATLAB R2013a, running on a computer with 2.6GHz and 2GB of RAM under Windows 7(32 bit) system.
Karimi et al. [55],	Journal of Super Computing	• Using data mining techniques and genetic algorithm in service composition	• High scalability • High efficiency • Low time	• High overhead • No sufficient attention to the fitness function	• Simulation by VC# 2013 language on Intel Core2 DUO, 2.5 GHz with 3 GB RAM

Table 3 (continued)

Authors and Date	Journal/Conference	Main Idea	Pros	Cons	Evaluation
2016					
Lartigau et al. [39], 2015	Journal of Production Research	• Using Artificial Bee Colony (ABC) for service composition	• High scalability • High efficiency • High optimization	• Time-consuming • Lack of user interactivity between model services and model provider limit reusability	• Simulation on Intel Core i3 CPU No tools mentioned
Huang et al. [48], 2014	Journal of Enterprise Information Systems	• New chaos control optimal algorithm for service configuration in CMfg	• Low time consuming • High performance • Find better solution s • The balance of exploration and exploitation • Suitable for large-scale cloud services	• High complexity It is unstable • Method convergence is under confirmation • Not implemented in real word	• Simulation experiments • No tools mentioned
Liu et al. [52], 2013	Journal of Computer Integrated Manufacturing	• Multi-composition for each task pattern to combine incompetent composite service into a whole	• High efficiency • High optimization • The high success rate of QoS requirement fulfillment • Low time	• Low scalability • No real implementation	• Simulation using MATLAB R2011b for windows, on a 2.50 GHz PC
Tao et al. [18], 2013	IEEE Transactions on Industrial Information	• Using data mining techniques and genetic algorithm for service composition	• High performance • High extensibility • Low execution time • Low energy saving • Low cost • Strong searchability	• No stability • No scalability • Need the user intervention to adjust parameters	• Simulation using two dual-core computers for a parallel environment • No tools mentioned

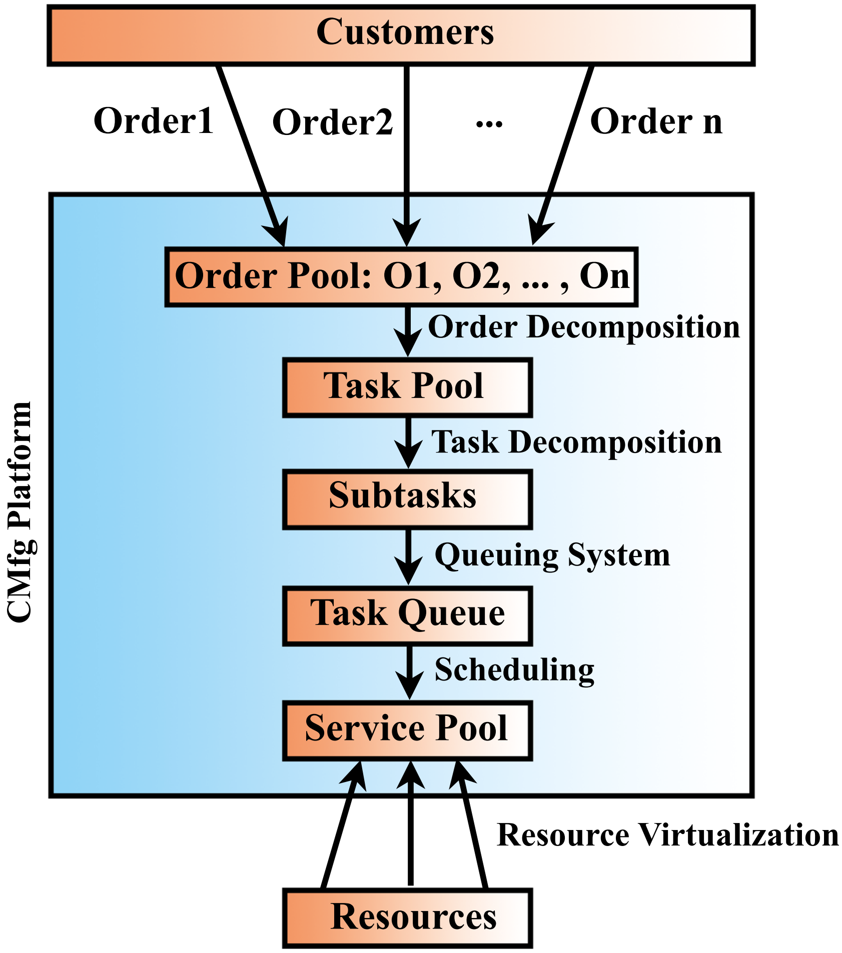


Fig. 6 Schematic diagram of multi-task scheduling in CMfg

Zhou et al. [70] considered various types of manufacturing tasks and addressed their scheduling issue in CMfg by presenting a mathematical model. A task scheduling and resource allocation technique for the cloud was proposed by Jiang et al. in [71] that operated on disassembly. Yuan et al. [72] proposed a multi-objective optimization scheduling model to improve the production efficiency of a reconfigurable assembly line in cloud manufacturing. Li et al. [73] introduced the scientific workflow management system which is an efficient tool to execute and manage big data, and beneficial to the scientific discoveries.

The investigated articles in the RASS category are analyzed in Table 4. In the table, we considered columns for authors and date, journal/conference, main idea, pros, and cons, as well as the evaluation techniques of the articles.

3.5 Studies aimed at service searching and matching

In CMfg, various kinds of virtual resources are placed into a service pool in a CMfg service platform after the encapsulation and description based on the service description languages such as simple HTML ontology extension, DARPA agent markup language, and web ontology language (OWL). Therefore, a successful matching between customer demands and manufacturing services is possible [6, 7]. To fulfill the requirements of providing the fit cloud service or service combination, a cloud manufacturing service discovery model was provided in [74]. The schematic diagram of the process of service discovery, matching, and composition is shown in Fig. 7. A number of researches addressing the service searching and matching problem were reviewed in this section.

Li et al. [75] proposed a new method for service matching in CMfg by analyzing the deficiency of the existing semantic web service and manufacturing grid service matching algorithms. Yang et al. [76] proposed a searching and matching mechanism based on semantic a similarity degree to locate the manufacturing resources and achieve accurate matching of resource service messages. The.

Wang et al. [77] proposed a framework based on semantic to address the resource discovery problem in CMfg environments. The authors combined the semantic web and OWL-S for their framework. Li et al. [78] investigated the service matching as a prerequisite for service composition. By proposing an extended service model and designing the reservation algorithm based on this model, they retained those

Table 4 An overview of studies aimed at resource allocation and service scheduling

Authors	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Akbaripour et al. [69] 2018	International Journal of Advanced Manufacturing Technology	• Solving the service selection optimization and scheduling by a mathematical model	• High performance • Considering transportation cost and time in CMfg • Using a mathematical model	• Do not consider the dynamic nature of CMfg • No considering service failure	• Cplex software on a 2.27 GHz CPU personal computer
Zhou et al. [70] 2018	Enterprise Information Systems	• Task scheduling in CMfg based on individualized requirements	• Providing a mathematical model for scheduling • Using a case study to show the effectiveness of the model	• No consider the correlations among tasks • No consider the dynamics of the CMfg environments	• Implemented by a case study
Liu et al. [56] 2017	Journal of Robotics and Computer-Integrated Manufacturing	• Providing a multi-task scheduling model by incorporation task workload in CMfg	• High performance • Satisfying time, cost, QoS, and service availability constraints	• Not considering the continuous arrival of tasks at different times	• Writing Monte Carlo simulation programs in C/C++ language using Visual Studio 2010
We et al. [58] 2016	Journal of Central South University	• Using a hybrid discrete swarm optimization- a genetic algorithm for multi-task scheduling	• High efficiency • High performance compare to existing algorithms • Scalable	• No implementation in a real cloud environment	• Simulation in MATLAB 2009a on a PC with 2.00 GH Intel Pentium
Zhou et al. [59] 2016	In Asian Simulation Conference Springer Singapore	• Providing a dynamic task scheduling method for CMfg	• Considering uncertainties in CMfg • Solve the problem of system state changing	• Needs a high-speed computational capability • Needs a high-speed network transmission • No implementation	• simulation experiments • No tools mentioned
Cao et al. [61] 2016	Journal of Advanced Manufacturing Technology	• Providing service selection and scheduling model using an Anti Colony with service, the selection mechanism	• Comparing the proposed method with existing algorithms • High convergence speed • Excellent searchability • High stability • High optimization • Suitable to handle massive concurrent data • Low time	• Not considering energy consumption • Lack of a comprehensive definition of product quality • Not considering the acceptable quality threshold	• Simulation experiments with several simplifying assumptions • No tools mentioned
Wang et al. [57] 2016	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science	• Providing a resource scheduling model in CMfg using Swap Shuffled Leap-Frog Algorithm (SSFLA)	• Comparing the proposed algorithm with existing ones • High convergence speed • High robustness	• Not Considering the dynamic behavior of physical resources	• Simulation in Matlab
Thekinen et al. [67] 2016	Journal of Manufacturing Systems	• Using matching theory in cloud-based design and manufacturing	• Matching supply-demand • Analysis of merits and limitation of a matching mechanism	• Assuming that the agents are substitutes and not complement • All agents may not provide an exhaustive list of their alternative	• Simulation experiments • No tools mentioned

Table 4 (continued)

Authors	Journal/Conference	Main Idea	Pros	Cons	Evaluation
				• No money change was considered	
Barenji et al. [65] 2017	Journal of Advanced Manufacturing Technology	• Providing a Dynamic Scheduling System for Manufacturing Flow Line using Multi-agent	• Considering dynamic order behavior, • Not tied to any specific model in the software platform • System functions robustly	• Needing a moderate knowledge of a developed system • High time	• Implementation by JACK, an agent-oriented programming language
Jiang et al. [71] 2016	Journal of Manufacturing Systems	• Providing a Cloud-based disassembly system	• Providing a mathematical model • Considering the uncertainty nature of the disassembly process • Multi-objective algorithm	• No consider the service quality	• Programming in R language
Yuan et al. [72] 2016	Optimization Methods and Software	• Improving the production efficiency of the reconfigurable assembly line	• Minimizing the cost of the assembly line and delayed workload • Production load equalization • Using a case study • High efficiency • Multiple different kinds of product	• It uses a static method instead of the dynamic or adaptive method	• Using a case study of the reconfigurable motor assembly line
Li et al. [73] 2016	International Journal of Advanced Manufacturing Technology	• Improving the efficiency and productivity of modern manufacturing	• Considering performance metrics: makespan, average resource utilization, load balancing level, comprehensive performance	• Do not have considered the system security • Assumed the heterogeneous systems are static	• Using Java for random workflow generator
Li et al. [60] 2017	IEEE Systems Journal	• Providing a CMfg scheduling model cooperative manufacturing in regional enterprise cluster	• High optimization • Providing various scheduling schemes • Comparing the strategies based on time, cost, performance	• Not considering task priorities and arriving patterns • Load imbalance • No real implementation • No analysis of logistics and inventory costs	• Numeric analysis of strategies using MATLAB
Cui et al. [66] 2015	International Manufacturing Science and Engineering Conference	• Resource allocation in CMfg using a K-means clustering and PSO algorithm	• Considering variable metrics • Efficiency • High speed for finding a global best solution • Optimization • Multi-Objective	• Not Considering reliability • Using static manufacturing service	• Simulation experiments • No tools mentioned
Cheng et al. [62] 2014	Journal of Applied Mathematics	• Resource integration and optimal scheduling in CMfg by considering correlation among virtual resources	• High performance with sharing of resources • Satisfying in the case of resources limitations	• Only the cost and time of QoS considered • Not considering reliability and trust • There is an invalid solution in solution space • Considering only one CMfg enterprise	• Using simulation for performing a scenario • No tools mentioned
	Journal of Simulation Modeling		• Low time and cost of the production task		• Simulation using MATLAB

Table 4 (continued)

Authors	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Jian et al. [64] 2014		• Batch task scheduling optimization model using improved PSO algorithm	• Scalable proposed • Comparing method with existing ones • High optimization	• Dealing tasks with the same characteristics and production process	
Lartigau et al. [68] 2012	Service Sciences International Joint Conference on	• Providing a framework for scheduling methodology in CMfg	• Considering a batch of tasks, quantity of resources • Focus on scheduling challenges	• No simulation or implementation	• Formalization of a scheduling problem
Laili [63] 2011	In Industrial Engineering and Engineering Management 2011 International Conference on	• Task scheduling using Energy Adaptive Immune Genetic Algorithm (EAIGA)	• Good searching ability • High performance • Improved stability • High-quality solution	• High time • No real implementation	• Simulation experiments • No tools mentioned

services with correlations in the candidate service set. Tai et al. [79] analyzed the properties and characteristics of manufacturing resources and demands, aiming to deeply study the resource supply and demand intelligent matching process.

Cheng et al. [80] studied the supply-demand matching hyper-network (*Matching_Net*). The proposed hyper-network addressed the challenge of the integration of diverse distributed manufacturing capabilities and resources in the form of manufacturing virtualized services in CMfg platform. Cheng et al. [81] proposed a novel method to address the manufacturing resource supply-demand matching problem. In their work, the specific key technologies for implementing the method were presented.

Sheng et al. [82] provided an intelligent matching engine based on the ontology language for service (OWL-S) for CMfg services in small and medium-sized enterprises. Guo et al. [83] proposed a framework based on agents to solve the problem of manufacturing service discovery.

The investigated articles in the SSM category are analyzed in Table 4. In the table, we considered columns for authors and date, journal/conference, main idea, pros, cons, and evaluation technique of the articles.

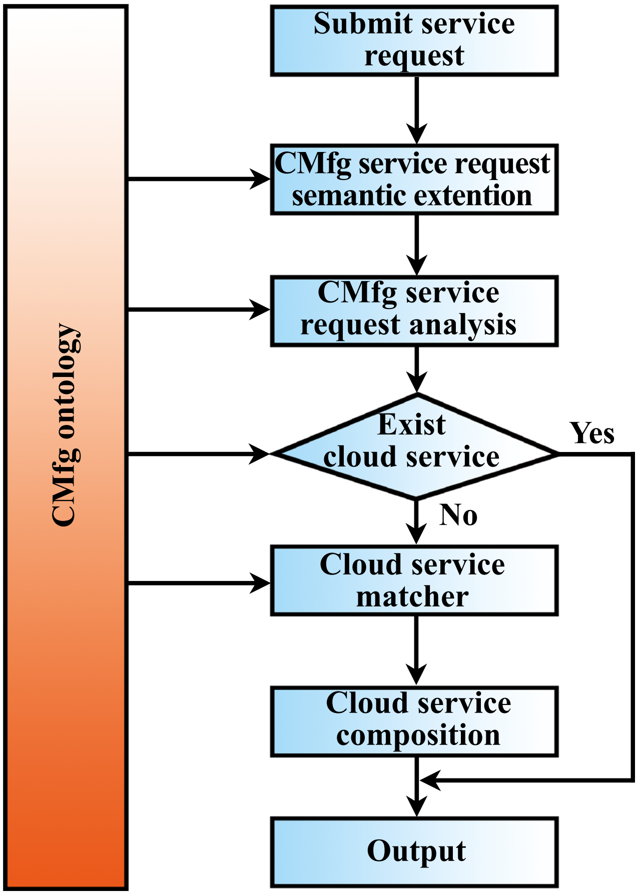


Fig. 7 Schematic diagram of the process of service discovery, matching, and composition

Table 5 An overview of studies aimed at service searching and matching

Authors and Date	Journal/Conference	Main Idea	Pros	Cons	Evaluation
Cheng et al. [80] 2017	Journal of Robotics and Computer-Integrated Manufacturing	• Using complex networks and hyper-network for supply-demand matching	• Using service correlations • Scalability • Low time	• For specific optimization problems need model modification • Using a static matching or mapping	• Simulation using MATLAB
Yuang et al. [76] 2017	Journal of Intelligent Systems	• Providing a searching and matching model based on semantic similarity degree	• Formal description of the resource • Matching problem transformed into a quantitative calculation • Improved accuracy and efficiency	• Not Considering resource demanding information perception • Not considering safety, security, and reliability • Not introducing technologies for data processing	• A case study
Cheng et al. [81] 2018	Enterprise Information Systems	• Resource-supply matching using complex network and IoT	• Extracting some requirements and characteristics of supply-demand matching issue • Scalability	• No real implementation in a cloud environment	• Implementation
Sheng et al. [82] 2016	Journal of Advanced Manufacturing Technology	• Service semantic matching and searching based on OWL-S	• Scalability • Using semantic similarity for service matching • Doing a smart matching	• High computation • No real implementation in a cloud environment	• Case study
Li et al. [78] 2015	In Systems, Man, and Cybernetics International Conference On	• Considering the Correlations among Services in Service matching	• Improved QoS of composite services • Avoid queue phenomenon of high-quality services • Multi-objective optimization	• High time • Large solution • Space • Inefficiency in searching	• Simulation using a Goal programming language
Guo [83] 2015	Journal of Advanced Manufacturing	• Service discovery based on agent	• Scalability, Extensibility • Timeliness • The method has a significant breakthrough in theory	• Parameters of the agent are a fixed value	• Simulation using JADE
Li et al. [75] 2014	In Control and Decision Conference, The 26th Chinese	• Using OWL-S for service matching In CMfg	• High accuracy and recall rate • Providing a stepwise matching process • Providing similarity measurement algorithms	• Not considering QoS properties • No implementation or simulation • No scalable	• Case study • No tools mentioned
Tai et al. [79] 2013	Journal of Advanced Material Research	• Algorithms for matching supply and demand using semantic similarity	• Considering resource and demand properties for matching	• No simulation • No implementation • High time	• Mathematical analysis
Wang et al. [77] 2012	In Computer Science & Education, 2012 7th International Conference on	• Resource description, matching strategy, and similarity algorithm	• Combines OWL-S with semantic web service • High recall and precision ratio	• Not considering digital equipment resource sharing	• Simulation with WSIL Explore tool

Table 6 Details of the papers not included in our classification

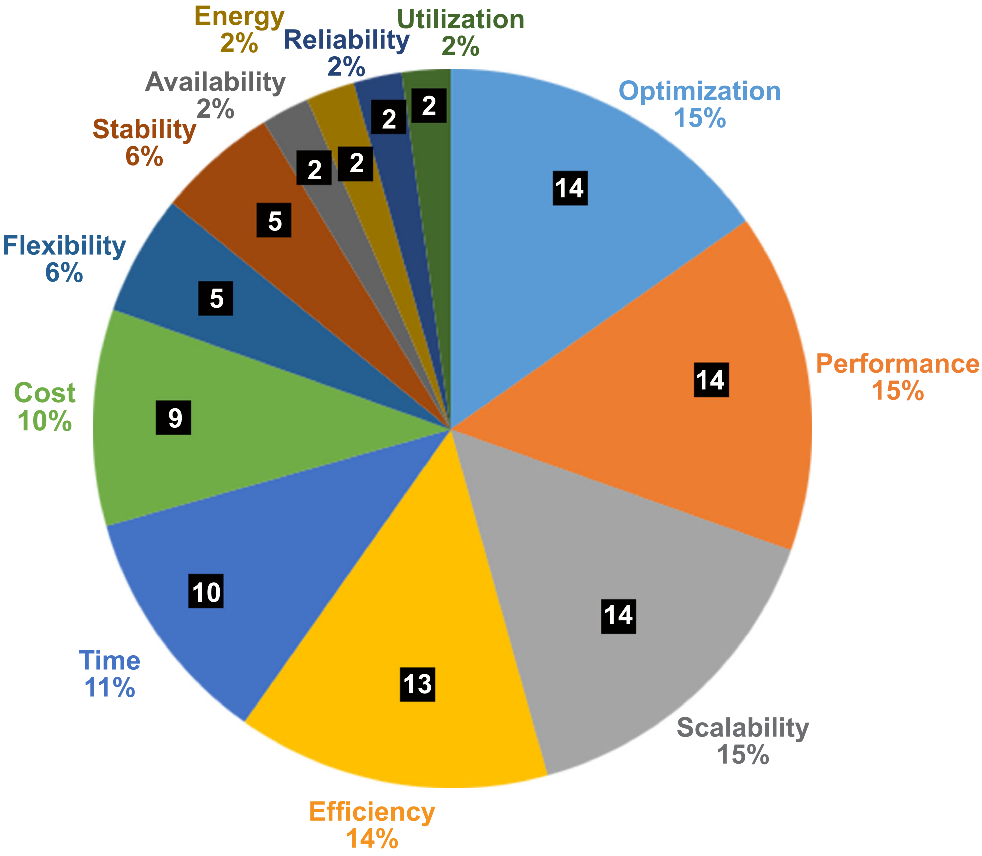
#	Publisher	Year	Authors	Journal/Conference	Type
1	Taylor	2015	Ren et al. [1]	Journal of Computer Integrated Manufacturing	Research
2	Elsevier	2014	Jula et al. [37]	Journal of Expert System with Application	Survey
3	Taylor	2014	Ren et al. [3]	Enterprise Information Systems	Research
4	Taylor	2013	Zhang et al. [13]	Enterprise Information Systems	Research
5	ASME	2013	Ren et al. [14]	Proceeding of ASME Manufacturing Science and Engineering Conference	Research
6	Taylor	2013	Xu et al. [15]	Journal of Multi-Disciplinary Engineering	Research
7	Elsevier	2016	Esmaeilian et al. [19]	Journal of Manufacturing Systems	Review
8	Elsevier	2013	Wu et al. [4]	Journal of Manufacturing Systems	Survey
9	Taylor	2014	He et al. [5]	Journal of Computer Integrated Manufacturing	Survey
10	Taylor	2015	Adamson et al. [6]	Journal of Computer Integrated Manufacturing	Survey
11	ASME	2015	Tao et al. [7]	Journal of Manufacturing Science and Engineering	Survey
12	Springer	2016	Tarchinskaya et al. [8]	Engineering Trends in Information Systems	Survey
13	Elsevier	2017	Chen et al. [20]	Journal of Robotics and Computer-Integrated Manufacturing	Research
14	Springer	2016	Liu [21]	Journal of Science Mechanical	Research
15	ASME	2014	Wang et al. [22]	Proceedings of ASME International Manufacturing Science and Engineering Conference	Research
16	Springer	2016	Kang et al. [12]	Journal of Precision Engineering and Manufacturing Green Technology	Survey
17	ASME	2014	Buckoltz et al. [23]	Journal of Manufacturing Science and Engineering	Review
18	Inderscience	2016	Yadekar et al. [17]	Journal of Agile Systems and Manufacturing	Review
19	Elsevier	2017	Jafarnejad Ghomi et al. [84]	Journal of Networks and Computer Applications	Survey
20	TransTech	2013	Yang et al. [74]	Journal of Advanced Materials Research	Research
21	Springer	2016	Kang et al. [12]	International Journal of Advanced Manufacturing Technology	Research
22	Elsevier	2010	Li et al. [9]	Computer integrated manufacturing systems	Research
23	SAGE	2017	Mitta et al. [85]	Journal of Engineering Manufacture	Review
24	Elsevier	2017	Li et al. [10]	Technological Forecasting and Social Change	Research
25	Elsevier	2018	Shadroo, et al. [11]	Computer Networks 139	Review
24	Taylor	2018	Kusiak, [86]	International Journal of Production Research	Research
27	Elsevier	2016	Mourtzis, e al. [87]	Procedia CIRP	Research
28	ACM	2012	Liu et al. [88]	Workshop	Research
29	Elsevier	2017	Chen et al. [89]	Robotics and Computer-Integrated Manufacturing	Research
30	Polska Akademia Nauk	2016	Zawdzki, et al. [90]	Management and Production Engineering Review	Research
31	Springer	2016	Rinugu et al. [91]	Software Quality Journal	Research
32	Elsevier	2015	Lee et al. [92]	Manufacturing Letters	Research
33	Springer	2017	Chang et al. [93]	Journal of Intelligent Manufacturing	Research

4 Discussion and statistics

In this section, we provide some statistics based on studied articles. In searching papers to review the CMfg area, we selected 94 articles based on the best relevance to our study. Among them, 61 papers were classified into five categories: 7 articles focused on the architecture and platform design of CMfg (DAP), 7 articles concentrated on resource description and encapsulation (RDE), 20 articles aimed at service selection and composition (SSC), 13 articles focused on resource allocation and service scheduling (SASS), and 9 articles concentrated on service searching and matching (SSM) that we analyzed them in Tables 1, 2, 3, 4, and 5. For statistical purposes, the details of the articles not included in our classification are shown in Table 6. Selected articles that were analyzed in Tables 1, 2, 3, 4, and 5 have checked about QoS parameters [84]. The results are presented in Fig. 8 and Table 7. Figure 8 shows the research focus share on QoS parameters as optimization (15%), performance (15%), scalability (15%), efficiency (14%), time (11%), cost (10%), flexibility (6%), stability (2%), availability (2%), and energy (2%). The number of papers focused on each metric is indicated in the corresponding slice of the pie chart.

Figure 9 shows the numbers and the percentages of articles in each category. As shown in Fig. 9, researches focus shares

Fig. 8 Considered QoS parameters in the selected articles



are 33% for service selection and composition, 30% for resource allocation and service scheduling, 15% for service searching and matching, 12.5% for architecture and platform design, and 12.5% for resource description and encapsulation. The number of papers in each category is indicated in the corresponding slice of the pie chart. Figure 10 shows the distribution of all studied papers based on the publication years. As shown in Fig. 10, the percentages of researches published are 4% in 2018, 22% in 2017, 31% in 2016, 15% in 2015, 11% in 2014, 10% in 2013, 4% in 2012, 2% in 2011, and 1% in 2010. The number of papers in each year is indicated in the corresponding slice of the pie chart.

The venue types of papers are shown in Fig. 11. As shown in this figure, the journal papers are 81%, conference papers are 18%, and the book appears %1. The absolute numbers of researches in each venue are shown in the corresponding slice.

Figure 12 shows the distribution of studied articles based on different publishers. As shown in Fig. 12, the percentage of the researches published 29% by Springer, 24% by Elsevier, 16% by Taylor, 10% by IEEE, 10% by ASME, 3% by SAGE, and 8% by the others. The absolute number of papers published by each publisher has shown in the corresponding pie chart slice.

Evaluation techniques used in the articles and the corresponding statistics are shown in Fig. 13. We divided evaluation techniques into seven classes: Implementation, Simulation using Matlab, Simulation with no tools mentioned, No simulation or implementation, Using C#, Using C++, and others. Article frequencies in each class are shown on the corresponding slice; 20 articles (33%) implemented their solutions, 12 articles (20%) simulated their proposed method using Matlab, 11 articles (18%) used simulation but no mentioned the tools, 4 articles (7%) have not simulated or implemented the proposed method, 2 articles (3%) used C# programming language, 2 articles (3%) used C++ programming language, and 10 articles (16%) used other tools.

In summary, the results from the statistical discussion in this section are as follows: current research has been less attention to the energy (Table 7), while due to incremental growth of IT-based infrastructures, it needs the future research to pay more attention to this metric. Resource allocation and service selection and composition are two issues that the literatures more focused on and need more attention in the future (Fig. 9). The publications about CMfg are growing increasingly (Fig. 10). Most of the studied literatures are published in journals (Fig. 11). Elsevier and Springer are two publishers with most papers in the field of CMfg and are suitable resources for researchers (Fig. 12). Most of the authors, for demonstrating their methods, implemented them (Fig. 13).

Table 7 Utilized QoS parameters

Authors	Energy	Time	Cost	Optimization	Utilization	Scalability	Availability	Efficiency	Stability	Reliability	Performance	Flexibility
Wang et al. [34]						•		•				•
Zhang et al. [29]				•		•						
Xu et al. [32]				•								
Lu et al. [35]			•									
Luo et al. [30]					•							
Lu et al. [38]												•
Zhou et al. [41]				•		•		•			•	
Zhang et al. [43]	•	•	•	•				•				
Li et al. [44]											•	
Li et al. [45]								•				
Zhou et al. [47]									•		•	
Kumar et al. [50]		•	•				•		•	•		•
Liu et al. [40]		•	•	•						•	•	
Zheng et al. [42]				•				•			•	
Liu et al. [46]					•							
Chen et al. [49]						•		•				•
Liu et al. [36]											•	
Zhang et al. [51]								•			•	
Xiang et al. [53]				•		•			•			
Seghir et al. [54]		•		•								
Lartigau et al. [39]				•		•		•				
Huang et al. [48]		•				•					•	
Liu et al. [52]		•		•				•				
Liu et al. [56]			•				•				•	
We et al. [58]						•		•			•	
Cao et al. [61]		•		•					•			
Li et al. [60]			•	•							•	
Cui et al. [66]				•				•			•	
Cheng et al. [62]											•	
Jian et al. [64]		•	•	•		•						
Laili et al. [63]									•		•	
Cheng et al. [80]		•				•						
Yuang et al. [76]								•				
Cheng et al. [81]						•						
Sheng et al. [82]						•						
Li et al. [78]			•									
Cuo et al. [83]						•						
Karimi et al. [55]		•				•		•				
Tao et al. [18]	•	•	•									•
Total	2	10	9	14	2	14	2	13	5	2	14	5

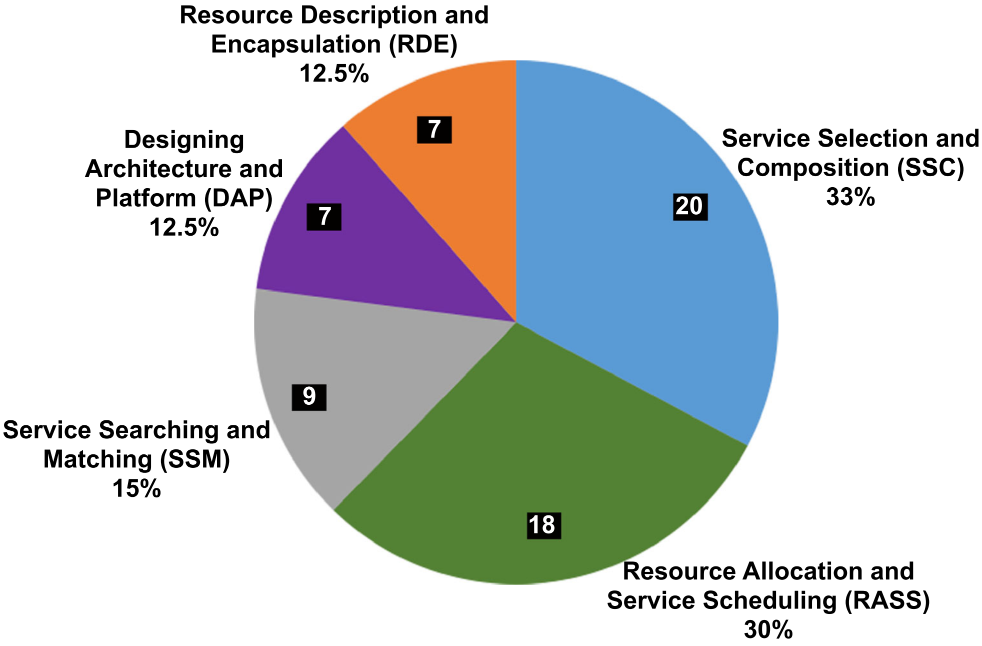


Fig. 9 Classification of studied articles

5 Open issues and future trends in CMfg

In this section, we provide a development diagram as a roadmap for future research and practice as well as open issues. As shown in Fig. 14, based on literature review, we found that CMfg has a great impact on three key sectors, including manufacturing, industry and economy, and marketing; it also faces to general issues such as standardization, load balancing, logistics, and cross CMFg services.

Manufacturing CMfg has changed the nature of manufacturing so that each phase of the full life cycle of manufacturing, namely design, simulation, fabrication, test, operation, and maintenance, was affected by it [25, 87–89, 91]. Smart manufacturing is another direction for future research [25, 87–89, 91]. Energy consumption and carbon emission are two important drawbacks due to the incremental growth of IT-based infrastructures, but a few studies analyzed these

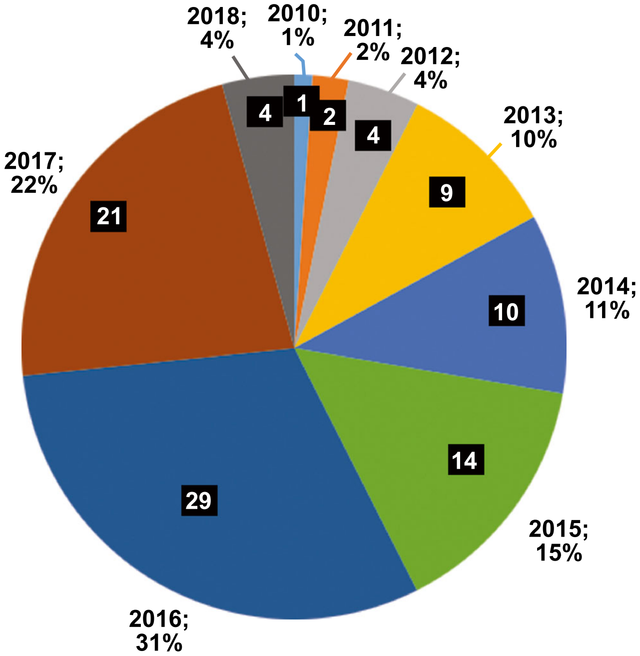


Fig. 10 The distribution of papers based on publication year

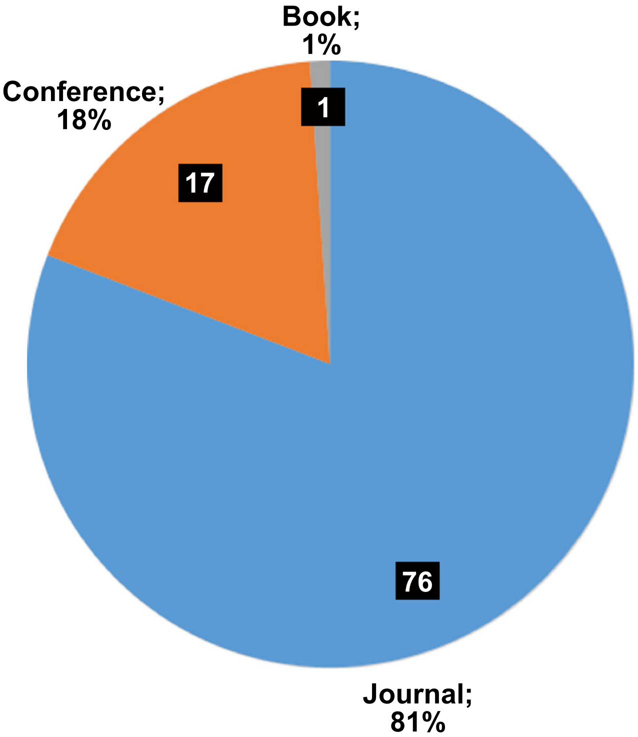


Fig. 11 Studies venue types

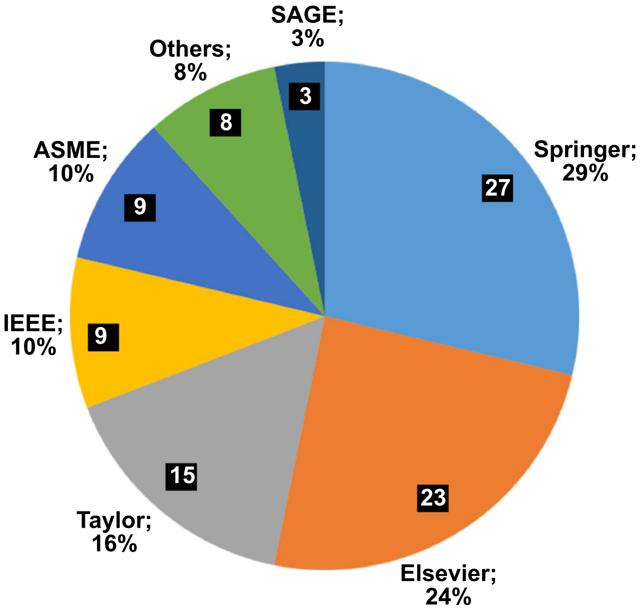


Fig. 12 Distribution of papers based on publications

two critical topics, as shown in Table 7. But, green computing that is a consequence of CMfg in the future will remedy the two drawbacks. By considering the current effects of CMfg, it is expected that the whole manufacturing process will be presented as a service. Although much progress has been made with regard to distributed manufacturing, distributed manufacturing environment [93] various complex issues must be considered. Smart manufacturing is under the influence of technologies like Cyber-Physical Systems [92], Internet of Things, smart products, and big data.

Industry With the convergence of new manufacturing processes and a new generation of IT, including cloud computing, cloud manufacturing, big data, mobile internet, artificial intelligence, Internet of Things, and RFID, in the manufacturing industry, a number of the country had put forwarded their advanced manufacturing development strategies. Among them are Industrial Internet and manufacturing system based on Industry4.0 in Germany, and China 2025 and Internet Plus Manufacturing in China. Although each of these strategies was proposed under different circumstances, one of the common purposes of these strategies was to achieve the interconnection, interoperability between the physical world and the information world of manufacturing and the intelligent operation of manufacturing. As one of the bottlenecks to achieve this purpose, the communication and interaction between the physical world and the information world of manufacturing must be solved.

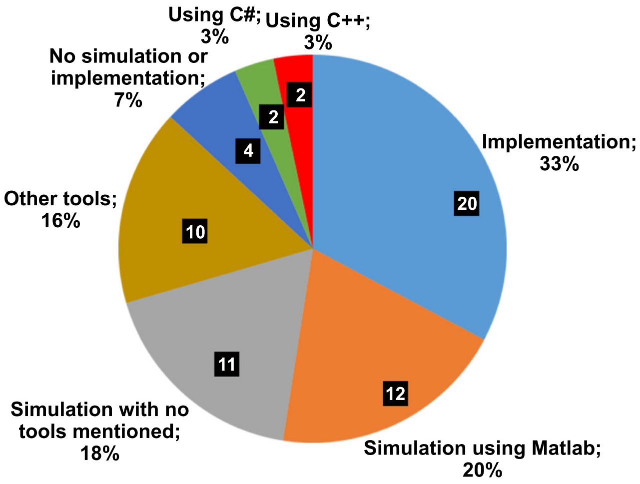


Fig. 13 Evaluation techniques used by articles

Actually, an interesting future trend is smart manufacturing with industry 4.0. Nowadays, the convergence of cutting-edge advanced ICT technologies is considered as the source of improving the competitiveness in the manufacturing industry. The fourth revolution in the manufacturing industry, smart manufacturing, which also considered as a new promising paradigm in manufacturing, through the introduction of various ICT technologies and the convergence with the existing manufacturing technologies, supports accurate and effective engineering decision-making in real time. Technologies such as Internet of Things, Cyber-Physical Systems, big data, sensors, cloud computing, and cloud manufacturing are key and enabling technologies for smart manufacturing. Changes in manufacturing systems, primarily IT-driven, especially towards cloud manufacturing, were described by industry 4.0 [12]. Industry 4.0 is an example of Germany's manufacturing strategy to compete in the new round of industrial revolution that focuses on industrial integration, industrial information integration, manufacturing digitization, Cyber-Physical Systems, Internet of Things, and artificial intelligence.

China manufacturing 2025 is a great revolutionary future trend in the manufacturing industry. Its guiding principles are to enhance industrial capability through innovation-driven manufacturing, optimize the structure of Chinese industry, emphasize quality over quantity, train and attract talent, and achieve green manufacturing and the environment. With cutting-edge advanced technologies, China's manufacturing growth has entered a new era. In response to the recent global reindustrialization tide and Germany's high-tech strategy "Industry 4.0", the State Council of China announced the "Made-in-China 2025" Plan in May 2015. This plan laid out strategic goals for economic development of the next 10 years from 2016 to 2025 [10].

Marketing In CMfg, it is possible the production manager, industrial engineers, manufacturing engineers, designers, and customers communicate with each other and therefore a co-creation process will form. In other words, CMfg will establish a new marketing channel for capabilities and resource sharing. CMfg has a great effect on reducing time to market and improving the quality of service.

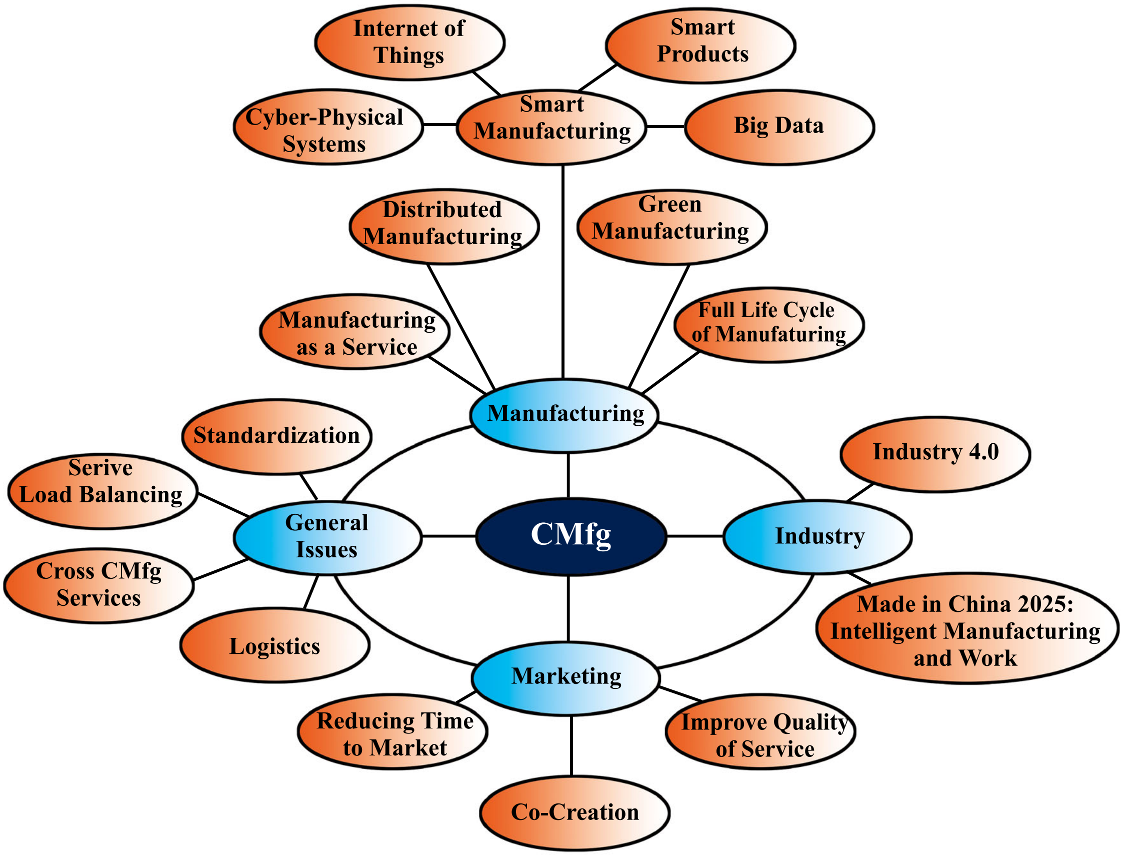


Fig. 14 Diagram for development, open issues, and future trends in CMfg

General issues In our literature review, we found that there is not a concrete definition for CMfg, while the existence of a definition by international institutes such NIST can show the way for future researches. Technologies such as semantic web and OWL-S provide a method for resource description but need to be standardized. In short, an international definition of CMfg, providing standards for CMfg architecture, resource description, and capability servitization would facilitate its development and implementation and generate better manufacturing solutions. Issues such as service scheduling and load balancing have drawn little attention, while these topics are important for QoS parameters, user satisfaction, and service utilization. Security and reliability also are two topics that require more attention. Another issue in CMfg is the large volume of data (big data) that needs data mining techniques to process them, for example, knowledge base in CMfg platform needs fast searching. With the continuous growth of CMfg, we will face cross-CMfg servicing and data lock-in problem; a single CMfg has limited manufacturing services due to both economic and technical constraints [17]. Recent studies on various aspects of CMfg, including its theory, architecture, resource description, scheduling, and service composition and the others, have increased the existence of diverse CMfg simulators. Another issue is the product pricing in an automatic manner, including the cost of designing, production, logistic, maintenance, and other services in the product lifecycle. Logistic time in CMfg is another issue that needs attention. Using a mathematical model for scheduling and service selection, taking into account load balancing, time, and cost could be a research direction in the future. Logistics optimization in CMfg needs broad attention.

As a new idea, we envision a possible impact of CMfg on the supply chain. Integration of CMfg and supply chain is another new trend and therefore it needs intelligent solutions for solving the emerging logistics and transportation issues. For example, using drones in CMfg environments and localization of services and manufacturing.

Another trend is the impact of CMfg on the world economy. It seems that in the future, CMfg encompasses the startups and in this way, it plays a critical role in the world economy. As the initial investment costs can be high for novel technologies, CMfg is essentially a cost-effective way for organizations and small- and medium-size enterprises which they will not face the risk of business investment.

6 Conclusion

Convergence of contemporary technologies, including information technology, cloud computing, manufacturing, the Internet of Things, and telecommunications, promised the emergence of CMfg. In this paper, we reviewed recent studies in cloud manufacturing and investigated the concepts, characteristics, and challenges that CMfg is facing with. Based on our investigation, we found researches on CMfg have advanced in five major aspects. Therefore, we classified the articles in five categories, i.e., (1) studies focused on the architecture and platform design of CMfg, (2) studies concentrated on resource description and encapsulation, (3) studies focused on service selection and composition (4), studies aimed at resource allocation and service scheduling, and (5) studies aimed at service searching and matching. In each category, we studied and analyzed a number of related researches and summarized them in tables. Authors and dates, main ideas, pros, cons, and evaluation techniques were metrics that we considered for provided models. While our study encompassed the advances, concepts, challenges, and characteristics of CMfg and provided a detailed analysis of research, it suffers from drawbacks: Firstly, it only surveyed articles published between 2011 and June 2018, which were extracted based on some search strings. Secondly, this study tried to investigate the articles published by famous publishers. There might be other publications, conferences, workshops, and symposiums which may be able to provide more comprehensive articles related to CMfg. Lastly, non-English publications were excluded from the study. For future works, resource scheduling and service load balancing in CMfg can be good candidates.

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