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ORIGINAL ARTICLE

A hybrid framework for integrating multiple manufacturing clouds

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Abstract Cloud manufacturing (CMfg) adopts and extends the concept of cloud computing to make mass Manufacturing Resources and Capabilities (MR/Cs) more widely integrated and accessible to users through the Internet. However, a single manufacturing cloud (MC) has limited MR/Cs, due to both economic and technical constraints, and can only provide limited manufacturing services in terms of function, price, and reliability, etc. Using the aggregated MR/Cs or services of multiple MCs is a natural evolution, i.e., MCs can satisfy peak demands for MR/Cs through collaboration, while users can have a wider selection of services from multiple MCs. To address such requirements, we propose a hybrid framework for integrating multiple MCs. The key functional modules and the business models of the proposed framework are presented to guide future integration of MCs. The enabling technologies, such as semantic web and ontologies, intelligent agents, service-oriented architecture, and materials handling and logistics technologies are also discussed. A case study is given, showing the feasibility and rationality of the proposed approach.

Keywords Multiple manufacturing clouds · Cloud manufacturing · Interoperability · Collaboration

1 Introduction

Cloud manufacturing (CMfg) as a new service-oriented manufacturing paradigm adopts and extends the concept of cloud computing [1] to make mass manufacturing resources and capabilities (MR/Cs) more widely integrated and accessible to users through the Internet [2]. A manufacturing cloud (MC) consists of heterogeneous MR/Cs and the CMfg management platform. Stakeholders of a MC can be classified into three categories: service provider, cloud operator, and service user. Service providers provide their MR/Cs as CMfg services in the MC. Cloud operators primarily realize efficient management and operation of CMfg services, which service users consume on demand. Significant research efforts have been made to analyze the connotation and system architectures and develop enabling technologies and typical applications of CMfg [3–6]. However, the scope of most current research has been limited inside a single and isolated MC [7]. The seamless integration of manufacturing resources, data, and capabilities on different clouds is still a research challenge [7, 8]. Similar requirements can be found in the areas of smart factory, smart home, smart building, and smart city, which are all in need of integrating services from different industrial clouds [9]. However, little work has been done on the integration of multiple MCs to date. The issue is critical and needs to be explored, due to the demands from both MC operators and users. MC operators have the needs to lease some MR/Cs from other MCs when their own provision is not enough during peak time, while users may want to find and use the most suitable services from multiple MCs.

This paper does not concern how a MC is built. The stakeholders may integrate their MR/Cs into the MC or own the CMfg management platform. Usually, either a company exclusively owns and operates the MC, or else the cloud operators of the MC are at the same time the main service providers. This paper assumes that there are several MCs. Literatures on

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multi-clouds [10, 11] inspired us; however, the MCs oriented to manufacturing industry have their own characteristics and domain-specific problems to address. This paper will try to address these issues and is organized as follows: Sect. 2 introduces the background and reviews related work; Sect. 3 presents a high-level view of the proposed hybrid framework for integrating multiple MCs; Sects. 4 and 5 elaborate two integration approaches under the proposed hybrid framework; Sect. 6 discusses enabling technologies; Sect. 7 presents a case study; Sect. 8 concludes the paper and discusses some future work.

2 Background and related work

2.1 Background

MC operators and users usually have different requirements, which call for different integration approaches.

2.1.1 Requirement of MC operators for the federated CMfg

The MC operators aim to continuously deliver CMfg services that can meet different quality of service (QoS) parameters of individual consumers, in order to maximize the market share. To achieve this, the operators should first guarantee sufficient provision of MR/Cs. However, in reality, this is hard, if not impossible, due to the technical and the market constraints. Rochwerger, Breitgand, Levy et al. [10] predicted that even the largest clouds may start facing scalability problems as the cloud usage rate grows. The MC will also face such problem. In the future, the problem may become even worse as more applications will be migrated into the MC. One solution would be to build several sub-MCs, like the Google or Amazon clouds. However, continuously expanding the scale of a MC is not a wise solution, as the manufacturing equipment usually costs more than the computing facility. The extra equipment to satisfy peak demands is largely left idle and consumes power, which could significantly impair the interests of MC stakeholders. Thus, a single MC will normally own limited MR/Cs, which are not enough during peak periods. Catastrophic or widespread failures of the MCs could worsen the resource shortage problem. Several cases of cloud service outrages, including ones of major cloud vendors, are reported in [11].

A good solution is to lease the MR/Cs dynamically from other MCs, when their own provision cannot meet user demands. This can not only enable some MCs to provide sufficient MR/Cs on demand but also maximize the utilization of other MCs' idle MR/Cs. The federation mode is a natural choice for the operators to use their aggregated capabilities and, meanwhile, maintain their independence.

2.1.2 Requirement of service users for diverse CMfg service options

Market competition will inevitably lead to multiple different MCs. Some MCs are better suited for a particular task than others. For example, a MC equipped with high-performance clusters can well handle large-scale simulation analyses of complex product designs, while a MC built for data-centric applications is good at storage and parallel processing of massive manufacturing data.

Generally, service users would like to acquire suitable services from multiple MCs by comparing the factors, like function, price, reliability, or cost-effect. For a simple manufacturing task, such as rapid prototyping, a 3D printing service can be enough. However, for a complex one, such as the development of a new product according to given requirements, design services, 3D printing services, experiment services, and some other services are needed to collaboratively achieve the task. Finding the "best" services from MCs for any complex task requires careful balancing among many parameters, which usually cannot be done manually. In such case, the optimization models and algorithms are necessary. Actually, what clients want the most is that after simple steps, they can get exactly what they want from massive, diverse CMfg services. Thus, service users need the service that can help identify proper CMfg services from multiple MCs.

2.2 Related work

2.2.1 Integration methods in CMfg

Significant research efforts have been reported on the integration methods in cloud manufacturing. Wang and Xu [12] presented a service-oriented, interoperable cloud manufacturing system (ICMS). The virtual function block mechanism and standardized description in this cloud-based environment are proposed to integrate existing and future manufacturing resources. However, the work mainly focuses on integrating MR/Cs into a MC, while the integration and collaboration issues between multiple autonomous heterogeneous MCs are not addressed.

Lu, Xu, and Xu [13] further proposed a hybrid manufacturing cloud (HMC) that enables companies to create different cloud modes (private cloud, community cloud, and public cloud) for their periodic business goals. HMC allows companies to define their own resource sharing rules for each resource so that unauthorized companies have no access to the resource. This research is actually more related to the resource sharing mechanism of enterprises' MR/Cs hosted in a MC.

Sun, Fan, Shen, and Xiao [14] proposed an ontology-based interoperation model to address the difficult issue of adaptively adjusting interface codes of existing systems and negotiating among multiple domains in collaborative product development (CPD). A similar method can be adopted in the integration of multiple MCs but needs to be further extended, as it is only suitable for the high-level architecture (HLA) [15] based CPD environment while MCs containing highly dynamic and heterogeneous contents call for approaches of dynamic ontologies and ontology fusion, which are not addressed in [14].

Inspired by the HLA standard, Fan and Xiao [16] proposed a federation-based integration framework of multiple MCs, to facilitate the sharing and collaboration of MR/Cs in heterogeneous MCs. The framework includes models for specifying common objects and their relationships, rules for MCs to achieve proper interaction, and interface specification of MCs. However, it lacks business models, i.e., basic motivations for the MCs to join a federation are not justified. The framework should be extended on the commercial dimension, such as billing, banking, and biding. In addition, it only deals with information flow while the logistics issues between multiple MCs are not addressed. Finally, the integration framework could not support to meet diverse user demands for suitable services from multiple MCs.

2.2.2 Integration of multiple computing clouds

Since there is no literature on integration of multiple manufacturing clouds, this sub-section reviews various approaches for integrating multiple computing clouds. Two types of delivery models in multiple clouds, federated cloud and multi-cloud, are identified in [11]. The federated cloud mode can enable multiple clouds to cooperate seamlessly through resource renting to maximize their mutual benefits [10]. Elmroth, Márquez, Henriksson, and Ferrera [17] outlined usage scenarios in the federated cloud environment and proposed an accounting and billing architecture. Toosi, Calheiros, Thulasiram, and Buyya [18] proposed the policies to increase IaaS providers' profits in a federated cloud environment. Multi-cloud refers to the usage of multiple and independent clouds by a client or a service [11]. Lucas-Simarro, Moreno-Vozmediano, Montero, and Llorente [19] presented scheduling strategies for optimal deployment of virtual services across multiple clouds. Montes, Zou, Singh, Tao, and Parashar [20] proposed a service framework that enables the autonomic execution of dynamic workflows in multi-cloud environments.

However, the integration of multiple manufacturing clouds (MCs) needs more efforts, as the CMfg accommodates much more than cloud computing [2, 3]. The integration of computing clouds mainly involves the information flow, while that of multiple MCs needs to further deal with the material flow and the capability service flow, because hard manufacturing resources (e.g., materials, machine tools, and robotics) and manufacturing capability (capability of accomplishing a particular task with competence, e.g., a design task and a production task) are also essential parts of the CMfg. Thus, the CMfg also needs enabling technologies, such as internet of things, big data, and artificial intelligence to address manufacturing issues. On the other hand, service contents are further expanded horizontally in the full life cycle of product manufacturing (containing design as a service, production as a service, maintenance as a service, etc.). Thus, the collaboration issues for integrating multiple MCs become more complex, involving more than information flow.

Thus, we need to explore the architecture for integrating multiple MCs. What the integration framework should be, and how the framework works with the cloud operators and supports service users are our concerns in this paper. This paper does not aim to propose very specific methods or algorithms for efficient collaborations between MCs, as different manufacturing industries or even different business problems have their own collaboration requirements. Instead, we only give out general approaches to guide the integration of MCs, and based on these approaches, corresponding methods or algorithms can be further developed according to specific industrial demands.

To facilitate presentation, we here explain differences between manufacturing resources (MRs) and manufacturing capabilities (MCAPs). Generally, MRs refer to the resource (e.g., cloud computing resource) that can easily be virtualized, servitized, and remotely operated (accessed) to serve widely distributed users through the internet. There are also some MRs that cannot be easily digitalized and directly handled by users, due to the reasons, such as high cost/too complex to adapt them as services, the operation of them requiring very professional skills and knowledge, the expensiveness, and vulnerability of them. For those MRs, they are usually provided as MCAPs, which usually involve both resource and people (or organization) with the know-how [21]. Thus, the granularity of MCAPs is relatively larger that of MRs, e.g., machining capability versus machine tools. The integration of MCAPs into MCs and the acquiring of MCAP services from MCs are mostly realized by the registration and (negotiation-based) transaction via MCs. After the registration, the collaboration of MCAP services can be achieved using information integration methods, just like that of MR services. The internal operations of MCAPs are usually hidden from consumers, while MR services from MCs can be used to provide MCAPs. However, co-executions of MR/Cs services to achieve a user task may both involve material flows besides information flows. Thus, we did not distinguish MRs and MCAPs any more to make the paper succinct.

3 A hybrid integration framework for multiple manufacturing clouds

As shown in Fig. 1, the integration framework consists of two integration approaches—federated CMfg and third-party CMfg—to achieve two disparate targets. The federated CMfg mainly concerns the integration of MR/Cs of different MCs to maximize federate vendors' interests, while the third-party CMfg acts on behalf of users to find best-fitting services

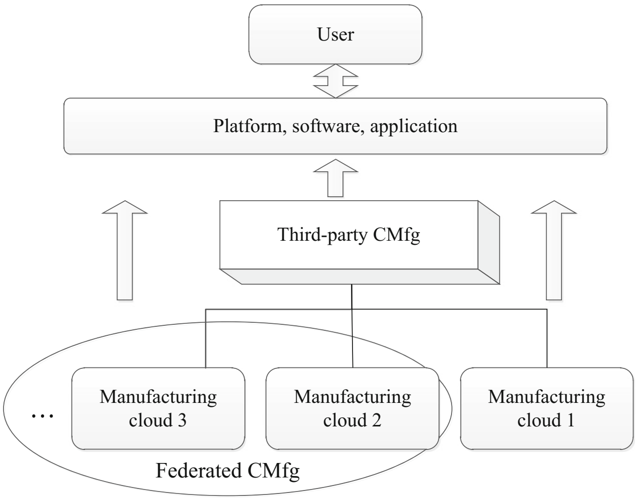


Fig. 1 A hybrid integration framework for multiple MCs

across different MCs. The MCs may or may not belong to a federated CMfg environment. Service users can develop their platform, software, and applications inside a MC or across multiple MCs through the third-party CMfg.

3.1 Federated CMfg

3.1.1 Characteristics

The MC operators voluntarily form a federated CMfg environment with seemingly infinite MR/Cs, so that the MCs can lease MR/Cs dynamically on demand from each other, to eliminate the effect of MR/Cs shortage and ultimately improve user experience. Such collaboration should be regulated by some common regulations, standards, and interoperability technologies to guarantee the orderly operation of the MC federation. The operators can still run the MCs autonomously, aligning with their own business targets on premise of obeying common agreements.

In case of MR/C shortage, the MCs in the federated CMfg environment need the ability of negotiation and coordination to rent MR/Cs. Transparency should be provided, as operators do not want service customers to know this and consumers do not want to be bothered by this. The QoS parameters can be guaranteed by the renting of MR/Cs in the federated CMfg environment, while the cloud operators can maximize their mutual benefits. The proposed integration approach to meet the above demands is presented in details in Sect. 4.

3.1.2 Business model

Each MC has the basic business model as an independent MC. Wu, Rosen, and Schaefer [22] performed a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis for the cloud-based design and manufacturing to understand what potential business model may fit. Chang, Wills, and De Roure [23] reviewed the cloud business models, which the CMfg is similar to.

The federation brings additional benefits to MC operators. First, operators can provide manufacturing services with satisfactory QoS, even during the peak time, so that they can increase user engagement and ultimately gain more profits. Second, operators can get part of the revenue through directly serving users. Once they encounter the shortage of MR/Cs, the MC will invite bids from others to rent MR/Cs and award contracts to the most suitable bidders. The MC can normally exploit the price difference between the chosen bids and user payment. Finally, the operator can make a profit when its idle MR/Cs are rented out.

3.2 Third-party CMfg

3.2.1 Characteristics

The third-party CMfg (TPCM) approach aims to meet the demands from service users, who need CMfg services to achieve their manufacturing tasks. The software platform that implements the TPCM approach is called the MC broker. Basically, the MC broker can collect data of the CMfg services from different MCs, extract useful information of CMfg services, classify the CMfg services according to different ontologies, and ultimately help the clients match most-fitted CMfg services where factors like function, price, quality, or cost-effect of services are considered. This is a loose integration approach, where the services of MCs are not integrated together, optimal service selection plans are provided for user tasks, but users need to work with different MCs to acquire needed services.

The tight integration approach on the other hand can offer the one-stop CMfg service for users by integrating and organizing services offered by different MCs. Besides information services, it further supports the workflow management to orchestrate diverse CMfg services from MCs to achieve user tasks. In such case, the complexity can be hidden, which allows users to work with services as if they belong to a single MC.

In either case, the MC brokers try to use service information or CMfg services from existing MCs to satisfy consumer demands, instead of building their own MCs. The proposed integration approach to realize MC brokers is presented in details in Sect. 5.

3.2.2 Business model

The primary motivation of a MC broker is to attract a massive amount of users. Then, they can make a profit by charging users directly, advertising, product recommendation, or cooperative discounts with real CMfg service suppliers. If the one-stop service is provided, they can make money by earning price differences. In addition, the MC broker may partner with some MCs and take a portion of the service provider's profit as remuneration once the user of the broker consumed service from partner MCs.

Overall, the hybrid framework involves the integration of MR/Cs based on two different approaches (federated CMfg (FCM) and TPCM), which differ in the degree of collaborations between the MCs involved and the way by which the user interacts with the MCs. There exists an agreement between different MCs in FCM, while in TPCM, there is no such agreement. The user interacts with a MC in FCM not knowing that the consumed services may come from other MCs, while the user is aware of the service provision from multiple MCs in TPCM.

4 Federated cloud manufacturing

4.1 Architecture

As shown in Fig. 2, the MC consists of the user broker, CMfg core service, coordination module, internal scheduling module, and monitor module.

4.1.1 User broker

The user brokers on behalf of service users negotiate with the MC. The MC will instantiate a user broker for every client to help identify suitable CMfg services. First, the user broker provides a customizable user interface that can adaptively fit users' pervasive devices and has the ability to percept user demands. Then, it can assist users to identify appropriate CMfg services based on their demands through queries and negotiation. For example, it helps queue for services and alert users when services are reserved or acquired. Finally, it offers execution support for users' applications, such as monitoring the progress of job execution and returning the results to users after job completion.

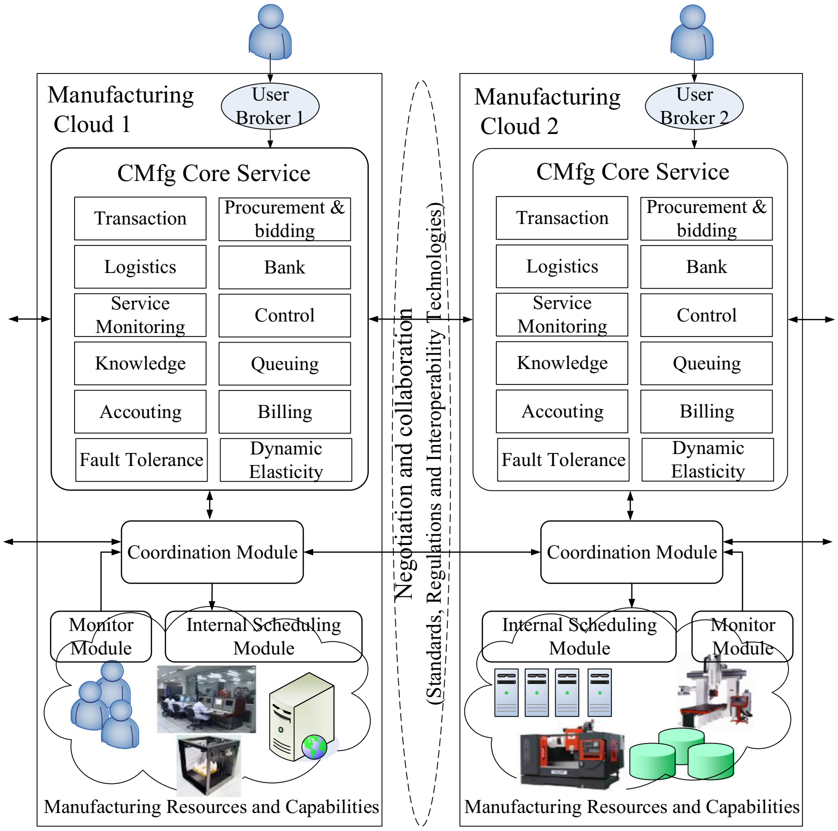
4.1.2 CMfg Core Service

- Transaction

  The transaction system (TS) provides the management services for e-transactions between users and the operator anywhere and anytime. It also supports the flexible transactions through negotiation, e.g., on the discount for heavy users.
- Procurement and bidding

  This is a vital part for the MC operators to lease MR/Cs when they do not have enough MR/Cs. When the underlying supporting system reports that the requested MR/Cs are not available, the procurement and bidding module (PBM) would issue a request for a certain amount of MR/Cs to other MCs in the federation environment. The

Fig. 2 Architecture of federated cloud manufacturing



PBMs of other MCs will bid to offer the leasing of MR/Cs. After receiving all the bids, the PBM will evaluate the offers and adopt the most suitable ones. At the same time, it will notify the results to the corresponding MCs and its underlying supporting system.

- Logistics

  There are material flows in manufacturing. A physical product cannot be manufactured without materials. The logistics module (LM) manages the internal flow of materials in a company, and external flow of products between companies and/or individuals.

- Bank

  The banking system offers financial services pertaining to agreements between users and the operator. The involved banks should be independent from both sides of the deal to promote the impartiality and trust. Other financial activities, such as the insurance or loan, also play a vital role in the development of the CMfg market.

- Service monitoring

  The service monitoring module (SMM) supports the collection and display of state information of manufacturing services to their consumers, so that users can track the progress of task executions. Advanced users would develop their own manufacturing platforms, software or applications that contain the decision-making modules based on the monitoring service.

- Control

  The control module provides services to configure and actuate various manufacturing services, such as virtual machine, storage, production machinery, and WSNs. For example, users may input control parameters and 3D models to the additive manufacturing service to make prototypes of their designs. However, users' right to control manufacturing services should be properly regulated to prevent unsafe operations. The malicious programs may also take advantage of this module and cause damages to the physical facilities. Thus, further research efforts are needed to delimit the border between the permitted rights and the prohibitive ones.

- Knowledge

  Knowledge plays a significant role in supporting manufacturing activities. Knowledge is accumulated and can provide assistance in every phase of a manufacturing process and the whole life cycle of a cloud service [21]. For example, knowledge can help on argumentation, design, simulation, production, experiment, maintenance, and recycling in a manufacturing process. Also, it can be applied to service description, publishing, matching, composition, trading, evaluation, etc.

- Queuing

  The requested CMfg service may not be available immediately, or the clients want to use certain services during certain periods. Then, the queuing module (QM) is necessary to support automated service reservations for users. Prioritized resource allocation should be supported for VIPs or emergent users.

- Accounting

  The accounting module (AM) records the actual usage information of CMfg services by requests, which is the foundation to calculate the total usage cost of each user. In addition, the stored historical usage information can be utilized for the purpose of third-party auditing and service quality improvement.

- Billing

  The CMfg specifies a business model that can benefit both service providers and users [24]. A significant characteristic is the pay-as-you-use scheme as utilities. The consumption of CMfg services is measured by calculating the actual usage. The billing module (BM) decides how service requests are charged, for example, submission time (peak/off-peak), or availability/quality of resources (supply/demand).

- Fault tolerance

  Fault tolerance can guarantee high availability and reliability of CMfg services, normally at the cost of more resource consumption. For critical applications, a short-time failure would bring great loss, for example, a failure in the control module hosted in the MC can damage the expensive CNC machine tool. Thus, the fault tolerance service is essential. However, for others where failures cause little effect, fault tolerance is not always necessary. So it all depends on the type of applications and user requirements.

- Dynamic elasticity

  The MC should provide the service for users to dynamically tune the parameters of MR/Cs (e.g., memory size of control computers and number of machine tools) allocated to users and the number of virtual execution environments to flexibly adapt to the changing load.

4.1.3 Coordination module

The coordination module coordinates the execution of the chosen CMfg services among different MCs, including data distribution for remote sub-task execution, retrieving local and/or remote results, and status monitoring and control of task execution. It virtualizes the management function of both local MR/Cs and remote MR/Cs from other MCs, to provide unified operation interface to CMfg core service (CCS), e.g., ID mapping of leased MR/Cs between MCs. It will not care about the pricing-related issues which are achieved by the procurement and bidding module.

4.1.4 Monitor module

The monitor module collects the information of the whole MR/Cs periodically, so that the upper layers can make decisions on whether to lease some MR/Cs and the amount of MR/Cs in need. The failure can also be detected and reported. The latest development of sensor and communication technology (in the area of internet of things, wireless sensor network, and wireless communication) enables the intelligent and dynamic perception of manufacturing related things and surrounding environment, thus promoting the optimal decision on various levels.

4.1.5 Internal scheduling module

The internal scheduling module is responsible for the allocation and controlling of MR/Cs belonging to the MC. It adopts the latest virtualization technologies [25, 26] to shield the heterogeneity of various CMfg MR/Cs. The virtualization of MR/Cs can provide both transparency and flexibility and enables the convenient organization of the MR/Cs for user tasks. The control of various heterogeneous actuators is included to operate manufacturing equipment and process materials.

4.1.6 Negotiation and collaboration

The negotiation and collaboration between the federated MCs are supported by regulations, standards, and interoperability technologies.

The regulations are high-level frameworks that determine the collaboration content and regulate the behavior of the federated MCs. For different manufacturing domains (e.g., electronics or appliance), the regulations may differ greatly, but fairness would be the general principle. They may evolve along with the technology advancement. The involved operators enact or revise them collaboratively through negotiation.

The standards are another important factor to facilitate the collaboration among different MCs. The standards can be about the technologies, frameworks, processes, and interface of interoperability, for example, the Standard for Exchange of Product data (STEP) [27] (or the extended STEP-NC) which is used to ensure product data interoperability throughout the lifecycle, and the HLA standard [15] in collaborative simulation of complex product designs.

Interoperability technologies (e.g., ontology and service-oriented architecture) are the detailed methods or techniques that are used to realize interoperability. It should comply with the common regulations and standards.

4.2 Dynamic MR/C leasing

We will explain here the leasing process of MR/Cs between MCs, with the support of functional modules in the FCM architecture (Fig. 3). The rough stages of such process are demonstrated as the flow chart in Fig. 4.

4.2.1 Determine the state of MR/C provision

(1) User broker (UB) parses the service description file submitted by the user and forwards the demand for manufacturing services to PBM. (2) PBM determines the needed provision of MR/Cs and forwards it to coordination module (CM). (3) CM gets the status of MR/Cs through monitor module (MM) and (4) checks whether the requirement for MR/Cs can be satisfied. If not, CM calculates the amount of MR/Cs that could not be provided in this MC. (5) CM returns the results to PBM. The user can get such feedback on price, utilizing way, etc. of services through UB and PBM.

4.2.2 Choose a plan according to user demands

Combined with the user choice (6), here exist three cases: abundant MR/Cs, and no enough MR/Cs for users' non-urgent need or urgent need. For the first case, 7^+ PBM will distribute the task to CM and 8^+ CM then forwards the task to internal scheduling module (ISM) for the real execution; for the second one, 7^- the requirement for MR/Cs will be submitted to QM and QM will queue for MR/Cs. The third case will be explained as the following since its processing is more complicated.

4.2.3 Lease MR/Cs from other MCs

(7) PBM will invite bids from other MCs. Correspondently, (8) the PBM of other MCs in the federation will ask CM whether the requested MR/Cs are available. Similar to the process (3)–(4), (9) CM will return the result to PBM. If another MC can lease required MR/Cs, (10) PBM offers the bid with QoS parameters, e.g., price or pricing method. After a certain amount of bids is received or the open time of bidding is due, (11) PBM of MC 1 will evaluate the bids and (12) tender contracts with the chosen MCs. Then, (13) PBM will issue the results to CM which (14) further tells ISM to reserve the needed MR/Cs. At the same time, (13^*)–(14^*) if the task (e.g., production task) involves material flows, the transport of materials/parts/semi-products between the collaborative MCs is needed, where LM comes into play. (15) CM of current MC will coordinate the co-execution or execution of all reserved MR/Cs for this task (this step contains the request and reply process to prepare all the input for the co-execution, e.g., the arrival of materials) and then (16) notify the start time of task execution to AM (responsible for recording service time). After some time, (17) ISM in MC 1 will return the execution result and, similarly, CM of other chosen MCs will also return the results. (18) CM will first notify the end time of task execution to AM and then (19) feed the complete result to SMM, which (20) delivers the results to UB.

During such resource leasing process, AM records the start time and the end time of resource utilization, so BM can

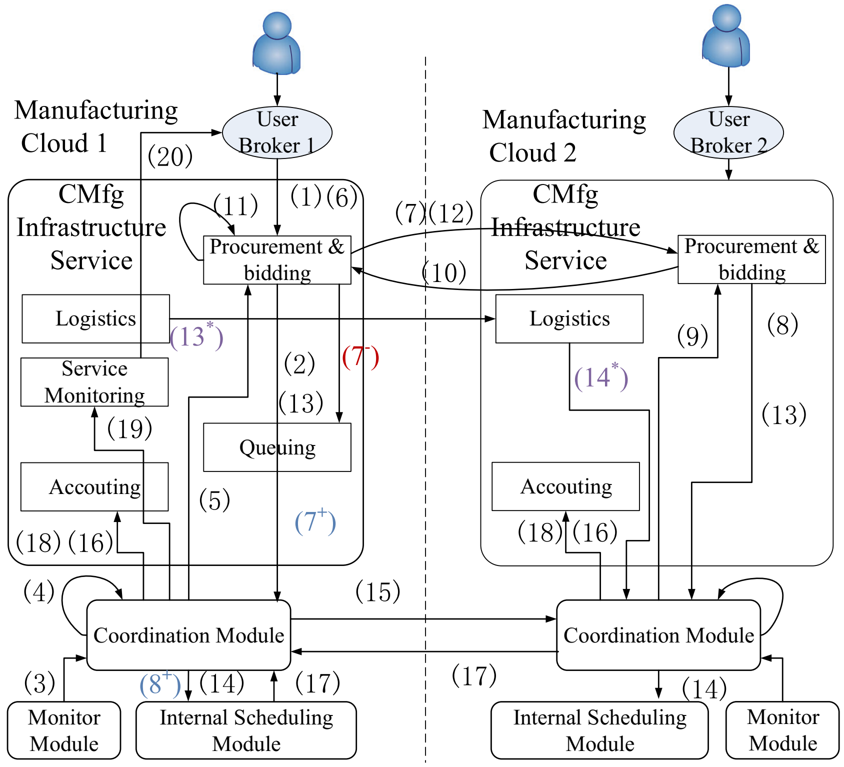


Fig. 3 Leasing process of MR/Cs between MCs

calculate the usage fee. After paying the MR/C rental fee according to the contracts, the MC can get the rest user payment as its earning. The negotiation process may be needed before tendering the contracts to achieve consensus on service level, pricing method, etc.

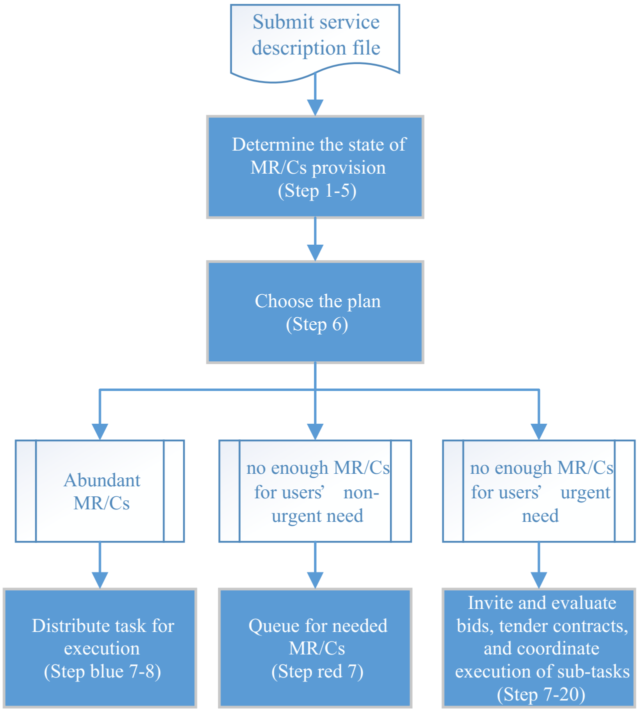


Fig. 4 Flowchart of dynamic MR/C leasing

5 Third-Party Cloud Manufacturing

5.1 Architecture

As shown in Fig. 5, the grey components inside the manufacturing cloud broker (MCB) only support matching service supply with user demand, which means that consumers have to access portals or user interfaces of corresponding MCs to acquire services. The highlighted components can supplement the grey ones to provide the one-stop service for manufacturing tasks.

5.1.1 UB

The user broker here fulfills similar functions like that in the FCM approach. However, it may be more complex, when the MCB only provides information service, and thus it needs to negotiate with several service providers to get satisfactory services for users. In such case, the UB needs a larger knowledge base. Comparatively, the UB that only needs to negotiate with the heavyweight MCB shows less complexity.

5.1.2 Manufacturing cloud broker

The manufacturing cloud broker is mainly composed of fourteen functional modules. The modules of bank, transaction, logistics, accounting, billing and queuing play similar roles as those described in Section IV. Thus their functionalities are not explained here.

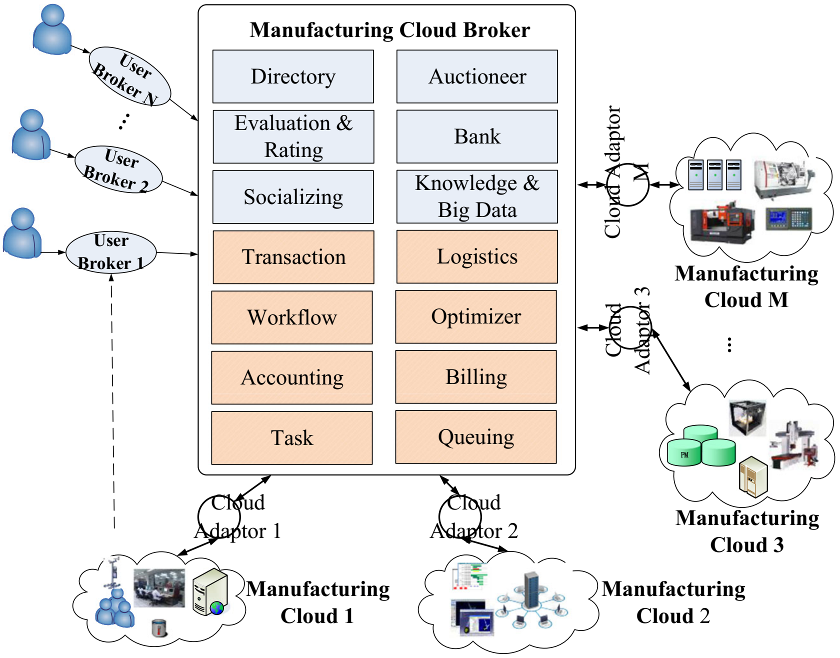


Fig. 5 Architecture of third-party cloud manufacturing

- Directory

  The directory module (DM) accommodates a list of the whole CMfg services that the MCs involved in the MCB can offer. It allows service consumers to browse the services using different classification ontologies, search for what they want, and check the information about the services.
- Auctioneer

  The auctioneers are responsible for clearing bids and requests received from the participants, i.e., both service consumers and providers. They are independent from the trading participants and need to be trusted by participants.
- Evaluation and rating

  This module supports users to evaluate and rate the services on the aspects of time, cost, reliability, credibility, function, etc., after service consumption. The evaluation and rating module (ERM) can help the service providers to improve the quality of their services, in order to attract more users and keep users' loyalty. This can also support knowledge extraction and assist users to know more about the services.
- Socializing

  Social networking is an effective way to build relationships [28]. Socializing plays a significant role in supply chain of manufacturing industry, as the companies tend to select familiar partners which may be more reliable and whose service price may be more favorable [29].
- Knowledge and big data

  The role of knowledge in the CMfg has been elaborated in Sect. 4. Comparatively, the MCB involves much more customers and providers with massive and various services or MR/Cs, so a large amount of manufacturing-related data are generated. Internet of things (IoT)-based manufacturing systems (e.g., production system, warehousing system, and logistics) and Internet (e.g., social networks, forums, and manufacturing outsourcing websites) all contribute to the production of big data. Big data [30], as a newly emerged methodology, can help analyze such massive data and extract information, knowledge, understanding, wisdom for manufacturing-related decisions, and actions [31].
- Workflow

  The workflow module (WM) allows clients to customize business or scientific workflows for complex applications, and can autonomously orchestrate the execution of dynamic workflows by elastically composing suitable CMfg services to satisfy user requests. It also offers to define and select scheduling policies of workflows, such as minimal time of completion and deadline-based policy.
- Optimizer

  The optimizer module (OM) can optimize the selection of services for dynamic workflows and for parallel execution of sub-tasks. It also supports the continuously automated and dynamic optimization of service selection to align with clients' targets (such as low price, less completion time).
- Task

  The task module (TM) enables users to manage their applications in the MCs, for example, the execution control of tasks and the initiation of new applications.

5.1.3 Cloud adaptor

The biggest difference with the FCM approach presented in Sect. Federated cloud manufacturing lies in that the MCs are integrated through distinct cloud adaptors in the TPCM approach. The MCs are passively involved in the trading and thus the necessary interface may not be available, so the cloud adaptors need to fill the gap between the MCs and various clients. Actually, the cloud adaptors may not represent the MCs (thus do not have the negotiation ability). They receive the request from the third party and respond through operations on the actual MCs. If the third party does not involve in the execution of user tasks, then the cloud adaptors need only crawl for information about services on the MCs.

5.2 Optimal selection of MCs' services

For simple tasks that can be achieved by a single service, a comparison may be enough for users to choose the most suitable service. However, things become more difficult when the user needs to select multiple services to accomplish the tasks collaboratively. We will then present how the suitable services can be found for complex tasks (as shown in Fig. 6):

(1) UB parses the service description file submitted by the user, and with the help of knowledge and big data module (KBDM) and user guidance, the task can be decomposed into several sub-tasks that need to be finished in certain sequence. (2) The ordered processes of sub-task execution are sent to and preserved by WM. (3) OM can find suitable services to accomplish each sub-task using (5) the data, information, or knowledge provided by KBDM. (4) KBDM can gather data or knowledge from DM, ERM, socializing module (SM), TM, and other sources of the internet or the real-time IoT systems. When there are important events occurred and identified, KBDM will actively notify OM to incur the optimization process for better selection of services.

For the one-stop mode, WM will drive the execution of the complex task automatically for users. In any case, the complex task can be finished by integrating services from diverse MCs. Cloud adaptors provide unified operational interface for WM to coordinate the execution of services hosted in different MCs. These services are optimally selected using the intelligent algorithms based on the optimization models. The service selection models for the production task should consider the transport cost and time of materials/parts/semi-products between production stages. According to [32], production logistics can occupy nearly 95 % execution time of the whole production process which has significant influence to the overall production efficiency. The IoT technology is pushing such selection process to be dynamic and iterative with real-time pervasive sensing ability, to ensure optimal performance under the dynamic execution environment. Mass services from MCs can be leveraged to counterbalance the effects of disruptions and uncertainties. Meanwhile, users can interactively involve themselves in such dynamic decision process to adjust the plans and optimally fulfill their tasks, such as changing the sub-tasks left to meet new market demand. Our next step would be the formulation of such problem and the design of efficient intelligent algorithms for this math model.

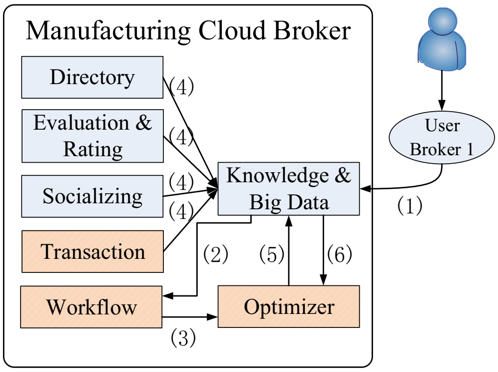


Fig. 6 Optimal service selection process

6 Discussion on enabling technologies

Interoperability is a key and inevitable issue in the integration of multiple MCs. An application whose parts are hosted in different MCs requires various degrees of interoperation and cooperation between MCs. In the FCM approach, MC operators may lease some MR/Cs to run parts of an application, while diverse services from different MCs are selected to collaboratively accomplish a user task in the TPCM approach.

For the purpose of good interoperability, high-level business models (e.g., accounting and billing model) and operation models of different MCs should first be semantically integrated, in order to provide integral services with good user experience. The reference mapping models should be built to guide the development of enabling technologies. Then, we will discuss the enabling technologies that can be utilized to facilitate interoperability.

6.1 Semantic web and ontologies

The semantic web provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries [33]. An ontology at the heart of semantic web framework is defined as an explicit and formal specification of conceptualization and their relationships. Ontology-based semantic integration technologies [34] in general will play a key role in achieving seamless connectivity between MCs.

First, a reference ontology should be built to facilitate mutual understanding and interoperability among multiple disciplinary domains, as the CMfg is in nature an inter-discipline, composed of several different domains, such as manufacturing, control, computing, and communication.

Second, even though inside the manufacturing domain, MCs oriented to different sub-domains, such as manufacturing of electronics or garments, may use different sets of terms. The CMfg ontology for different sub-domains may need further research, when multiple MCs are to be integrated.

Ontology-based inference may be needed to facilitate interoperation.

Third, the ontology of business models that are aligned with the MC operators' targets should be built to attain the full seamless integration between the MCs. Business models include pricing models, bug tackling strategies, security models, privacy models, and domain-specific models.

Generally, ontologies can facilitate the negotiation and collaboration among autonomous MCs through mutual understanding. Ontologies can help the MCB match services according to user demands. Classification and description models of services using ontologies can improve the searching efficiency and quality. Ontology-based inference can help acquire the exact user demand by interpreting the semantic description of their demands. Basically, the ontologies should be commonly accepted and easily extensible, as the MCs evolved dynamically.

6.2 Intelligent agents

Intelligent agents as autonomous entities can observe through sensors, act upon an environment using actuators, and direct their activities toward achieving goals. They can learn knowledge, adapt themselves to the environment, and coordinate and negotiate with each other toward a common goal.

Brokers in the FCM and the TPCM approach should employ the intelligent agent technology to interpret user demands and negotiate on behalf of users with the MCs or the MC broker to acquire appropriate services. Intelligent agent technology is also used by the procurement and bidding module and the coordination module to collect information, issue requests, bid, negotiate, and collaborate with each other. The learning ability of intelligent agents is important as the brokers may need to fast respond to the user request by preserving user cases, inferring user request and pre-searching results from the virtual MR/Cs pool according to users' information. There should be intelligent agents that can act for the MC brokers to query, request, or acquire services from different providers. Their ability to negotiate, collaborate, self-configure, and tolerate fault should be further explored under the environment of multiple MCs.

6.3 Service-oriented architecture

Service-oriented architecture (SOA) [35], a design for linking business and resources on demand, is a promising solution to facilitate the interoperability between heterogeneous MCs. Adopting the SOA concept in the design of MCs has obvious advantages for integrating MCs

6.3.1 Dynamic registration, discovery, and invoking of CMfg services

Based on SOA, service providers and cloud operators can register and offer their functionality as CMfg services in the MCs; service users and operators of other MCs are able to discover services hosted in the MCs at runtime and invoke the discovered services dynamically. In other words, new CMfg services can be dynamically added and published and the consumers can quickly get access to them.

6.3.2 Good interoperability and loose coupling between MCs

SOA-based MCs will have good ability of using different platforms and languages to communicate with each other. Interoperability between MCs is achieved through a standard message-based communications model defined in SOA. The MCs can provide an interoperation function as a service with an interface that can be invoked through a common payload format and protocol. SOA enables loose couplings and the idea of a few dependencies between MCs.

6.3.3 Convenient evolution of CMfg service implementation

MC operators can provide fixed interface on leasing MR/Cs based on SOA. The implementation of the interface can be upgraded without other operators' knowledge. Moreover, new interface can be dynamically added to increase interoperation ability. Similarly, the CMfg service implementations in both FCM and TPCM approach can also be altered without the users' knowledge.

6.3.4 Good composability of CMfg services in different MCs

Multiple SOA-based MCs host services of various granularities on different layers. The modular structure of each CMfg service enables them to be assembled into applications that can fulfill complex manufacturing tasks. Then, multiple MCs are able to cope with more complex manufacturing tasks. For example, the service-oriented sensor webs [36] owned by different MCs can be used collaboratively to collect the information of logistics.

6.4 Materials handling and logistics technologies

One significant difference between CMfg and cloud computing is that whether material flows are involved. The interoperability problem not only exists between the information systems of the MCs but also exists between the logistics and the information systems. The production tasks are sometimes rescheduled for different reasons (e.g., reducing production time and failure of the production system), or parts of complex products are (possibly sequentially) manufactured in different sites and assembled in one place, so the scenarios of transporting materials from a MC to another are common.

Thus, to facilitate the portability of manufacturing tasks among different MCs, the logistics systems should have the ability to interoperate. The automated packing and unpacking of materials should be supported by the MCs. Then, both the source and the destination MCs should be able to sense the information (such as number, price, and quality) of materials that are transported. Related technology includes the radio-frequency identification (RFID), the electronic product code (EPC, a scheme for the universal identification of physical objects), the object name service (ONS), and sensor technology [37].

7 Case study

The case study is performed in a conglomerate which designs and manufactures multi-disciplinary complex products. According to different roles played in the research and development (R&D) of complex products, the conglomerate is divided into multiple institutions. The institutions operate their manufacturing activities as well as their own sets of MR/Cs independently aligning with their own goals—designing and manufacturing sub-systems of complex products. Two problems arise in such organizational structure, impeding the improvement of efficiency. First, MR/Cs owned by different institutions are isolated from each other, even though much can actually be shared. This leads to low utilization ratio of MR/Cs. A common case is that the professional in an institution has to wait several weeks for MR/Cs services while the same MR/Cs services are left idle in other institutions. The FCM platform can help increase the utilization of MR/Cs inside the conglomerate, as some of the institutions own industrial clouds which integrate MR/Cs inside the institutions. Second, the institutions should learn to employ core competences of other institutions/enterprises while focusing on their own core businesses, instead of investing a large amount of money and time to develop such new capability by themselves. The TPCM platform can collect information of services provided by the institutions' MCs or other public MCs and offer the chance to match suitable CMfg services for the institutions to outsource non-critical tasks or hard tasks to the professional institutions or companies. Also, the institutions can get benefits by selling the service of their surplus MR/Cs on the TPCM platform.

7.1 Implementation of FCM environment

We have implemented a prototype of the FCM environment, which consists of several data centers inside the conglomerate. The data centers are used to perform simulation analyses of aerodynamic and structure designs of complex products during the R&D stage. Each data center mainly consists of a high-performance cluster (tens of teraflops) and the virtualization management system (VMS). The VMS containing three modules in FCM—UB, MM, and ISM—originally works as an integral system to serve its customers using the MR/Cs in a single MC. To implement FCM, we further developed CM (based on the existing MM) to coordinate the co-execution of sub-tasks across MCs; QM to queue for MR/Cs on behalf of users; PBM to bid, invite bidding, and evaluate bids to determine the distribution plan of sub-tasks/tasks among MCs; AM to record the usage information; and SM to monitor the status of service execution. The evaluation of bids currently only considers the state of the bidders' computing resource, i.e., bidders offer the usage information of their computing resource (e.g., node list<status, jobs, CPU, memory>and availability of requested MR/Cs). The integration work is still on-going to include pricing models, LM (by integrating services of third-party logistics and/or directly digitalizing current logistics resources), and address security and privacy issues. The implemented FCM framework can enable dynamic leasing of MR/Cs between industrial clouds, facilitating the resource sharing and improving utilization rate.

The algorithm designed according to the proposed leasing process of MR/Cs between MCs is shown as Fig. 7. For any manufacturing task, it (1) can be finished in unpredictable time, or (2) can be finished in predictable time but without time limit, or (3) needs to be finished in predictable time and within designated windows. We assume that any task can only belong to one of the above three types and compute the availability of requested MR/Cs from other MCs according to their types (as shown in Fig. 7). Then, PBM can determine whose MR/Cs to borrow.

Figure 8 shows the state information of two autonomous data centers that are integrated using the FCM approach. The data center #1 displays such information, while the data center #2 bids by reporting the usage information of its computing resource.

Figure 9 presents the transparent user interface for users to submit an aerodynamic analysis job using the ANSYS Fluent software. Users do not know where the batch job is executed. The job can be executed in data center #2, when data center #1 does not have enough computing resource.

7.2 Implementation of TPCM environment

We have developed a prototype of the lightweight TPCM framework (Fig. 10) to collect information about MR/C services from data centers in the conglomerate and provide the demand–supply matching service. Six preliminary modules—DM, KBDM, TS, BM, AM, and TM—have been included to support registration, searching, trade of services, recording of service consumption, and task management. KBDM contains ontologies for categorizing CMfg services (used by DM), rule-based expert knowledge, product models, etc. This platform which has been deployed in a conglomerate's data center can not only promote the MR/Cs sharing between internal institutions but also boost the outsourcing between the conglomerate and other companies to take advantage of each other's core competences. The data center has integrated hard

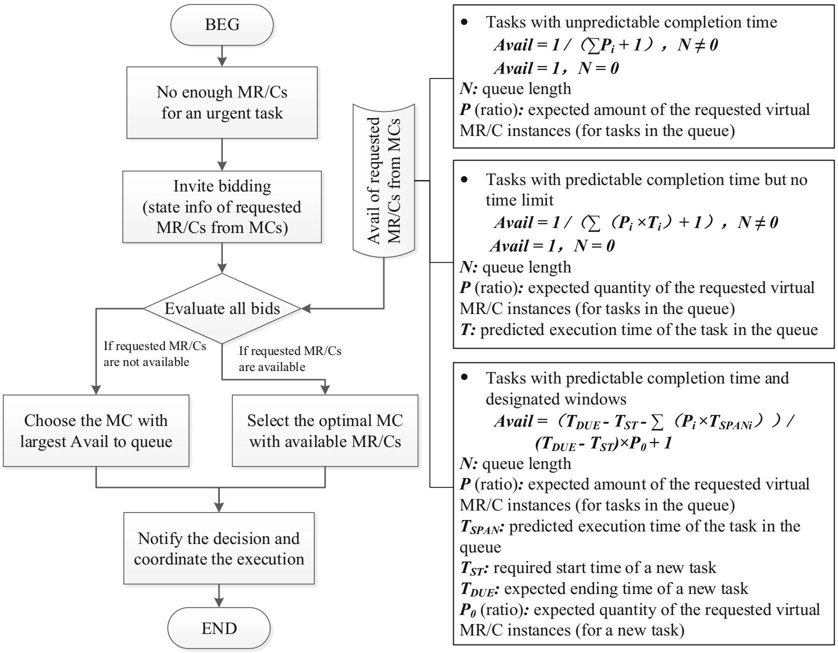


Fig. 7 Leasing process of MR/Cs between MCs

manufacturing resources, such as manufacturing facilities (Fig. 11) to share their surplus production capability.

Various kinds of machining capabilities offered by data centers and demand–supply matching service are shown in Fig. 12. These CMfg services include cutting, laser processing, surface finish, electroforming, and milling. The matching services, implemented in the platform, are also shown in Fig. 12.

7.3 Observations and discussions

Several observations have been made through the development of the proposed framework.

For the first approach, all the data centers affiliating to different institutions can still carry out their businesses independently, i.e., they build a loose coupling collaboration relationship without rebuilding their normal operation routine. Local user's interest can be guaranteed by assigning high priorities and reserving a certain amount of local MR/Cs. Such decentralized solution is also more robust than building a single MC, as a malfunction occurred in a MC does not interrupt the normal operation of others. On the other hand, the load can be well balanced among aggregated MR/Cs. When the local MC does not have enough MR/Cs, it can dynamically apply for MR/Cs leasing from other MCs. The MR/Cs here include the computing resources, software licenses, storage resources, and production facilities. During the R&D stage of a new

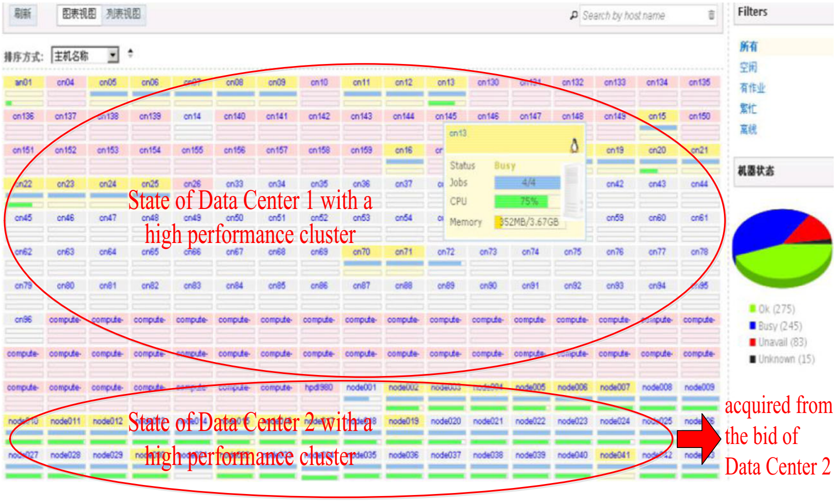
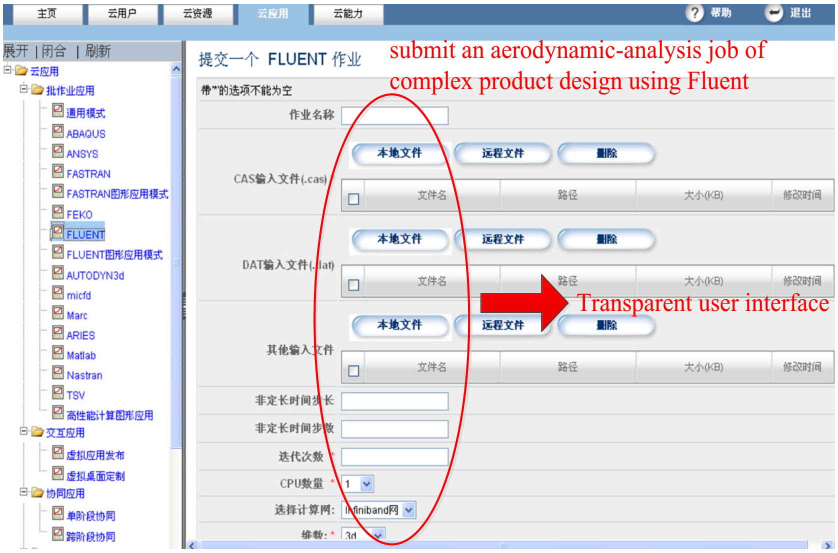


Fig. 8 State information of computing resource



提交一个 FLUENT 作业

带"*"的选项不能为空

作业名称

CAS输入文件(.cas)

DAT输入文件(.dat)

其他输入文件

非定长时间步长

非定长时间步数

迭代次数 *

CPU数量 * 1

选择计算网: Infiniband网

维数: * 3d

Fig. 9 User interface of aerodynamic analysis in data center #1

complex product, hundreds or thousands of the simulation analyses of aerodynamic and structure designs are needed and each analysis may take several hours in average. Without the federation, a data center may have long waiting lists of tasks while some others have much idle MR/Cs. After the introduction of the FCM approach, the average time spent on one round of simulation analysis has been reduced from 1 month to 1 week. At the same time, the utilization rate of MR/Cs is increased by 5 % in average, bringing significant savings.

The TPCM approach can help institutions identify and employ unique core competences in the form of manufacturing services inside the conglomerate to satisfy their manufacturing demands. For example, some institutions once found and consumed machining services with very high precision and special coating services for complex products (working in harsh environments), offered by others, through the prototype of the TPCM framework. Institutions do not want to invest money and time (probably in a large scale), due to the temporal, emergent, and rare use of these MR/Cs. As complex products usually work in harsh environments, the conglomerate owns some advanced technologies that are superior and can be transformative factors in other enterprises. The prototype currently only supports the matching service for simple tasks. In the future, we will develop mechanisms and algorithms to optimally match manufacturing services from MCs for complex tasks. And, external industrial clouds should also be integrated into this platform, to enable the outsourcing in a wider range.

8 Conclusion and future work

The CMfg as one trend of manufacturing moving toward digitalization attracts much attention since it has been proposed in [2]. Like cloud computing, it has good business models and there will be several MCs. However, little effort has been made to the collaboration issues between MCs. To fill this gap, we proposed a hybrid framework for integrating multiple MCs. The contributions are as the following:

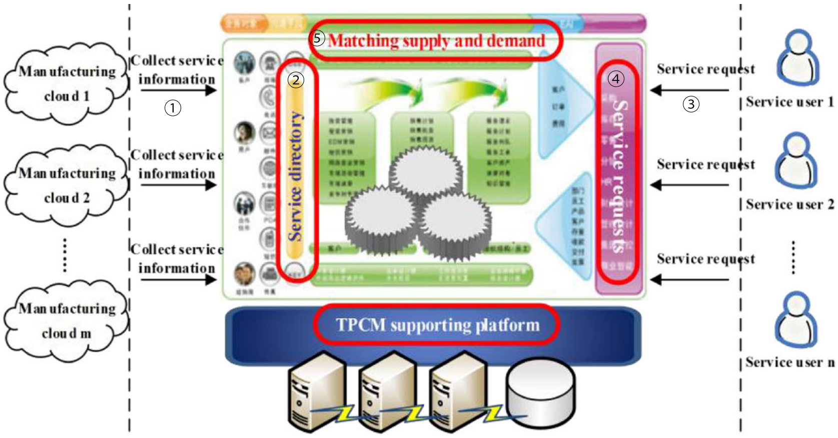


Fig. 10 Prototype of the lightweight TPCM framework

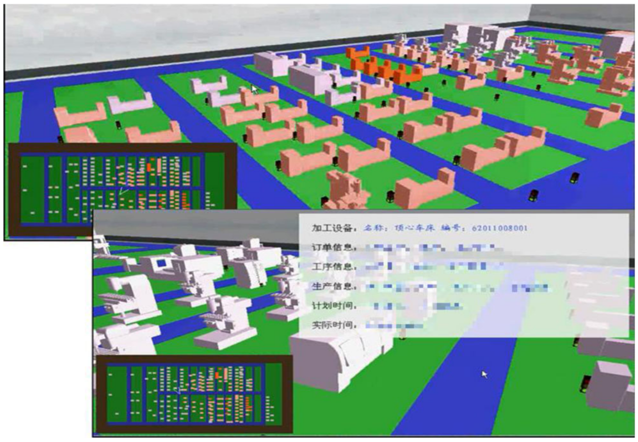

加工设备：名称：顶心车床 编号：62011008001
订单信息：[redacted]
工序信息：[redacted]
生产信息：[redacted]
计划时间：[redacted]
实际时间：[redacted]

Fig. 11 Three-dimensional visualization of machine tools in a MC

1. A holistic framework for integrating MCs

   A MC primarily realizes efficient management of its MR/Cs and provides CMfg services for service users, so the integration of MCs will mainly involves MR/Cs and CMfg services. The framework that we proposed provides a holistic solution to integrate MCs based on two approaches—FCM and TPCM—to satisfy the demands from MC operators and service users, respectively. The FCM environment can help MC operators to cope with peak MR/C demands using aggregated manufacturing utility of all the federated MCs, while the TPCM approach offers diverse choices of CMfg services from multiple MCs to better accommodate different user requirements. The high-level framework does not assume any implementation methods and combines the two approaches in a smooth and seamless way to cover the requirements from both cloud operators and service users.
2. Bidding-based loose integration approach for MR/Cs of MCs

   The current work mostly concerns the integration of MR/Cs into a MC but seldom solves the integration problem of MR/Cs from multiple MCs. Fan and Xiao [16] firstly proposed an integration model, by adopting the HLA concept of the federation. However, HLA only deals with the collaborative execution of distributed simulation codes (material flows are neglected) and do not have business models. We proposed a bidding-based loose integration approach that considers both logistics and business dimensions. Such FCM approach can provide a seemingly infinite manufacturing utility for each federated MC. On the other hand, the business model is very important and can determine the success of such integration approaches. Based on the bidding agent model, our approach can maximize the mutual benefits of federated MCs, while MCs can still maintain autonomy and operate aligning with their own business targets. Moreover, the specific implementation methods are not constrained and can be flexibly designed in our approach.
3. User-centric integration approach of services from MCs

   Previous work mainly focuses on the integration of manufacturing services in grid environments, which do not have good business models. The services provided by different MCs usually have different features, such as functions, QoS, pricing strategies, and cost-effect. Thus, we proposed a user-centric integration approach of services from MCs, to help users find and acquire the most suitable CMfg services from multiple MCs. Social network and big data are considered in the approach to make the evaluation of service selection plans more accurate, for example, using multi-source and huge volume of structured and unstructured data (e.g., the comments and chats about CMfg services on the Facebook and on the

Fig. 12 Service searching on the TPCM platform


在线能力列表

切削加工
能力名称：切削加工
技术队伍：核心技能人才（10%，高级技师以上）、骨干技能人才（15%，技师）、重要技能人员（30%，高级工和助理技师）和一般技能人员（45%，中级工）
加工能力：大行程机加30H/天，精密机加30H/天，普通机加2400H/天
企业资质：GJB9001B-2009

切削加工
能力名称：切削加工
技术队伍：研究员 20 余人，高级工程师近 200 人，技术工人406人
关键设备：数控五面加工中心XK2414、四轴立卧加工中心DMU100P、五轴加工中心DMU100P
加工能力：大行程机加30H/天，精密机加30H/天，普通机加6000H/天

大型龙门铣、龙门磨加工
主营：电气机械及器材制造业

v.cosimcloud.com/tianzhi/cloud/c
首页 请登录 | 注册
帮助中心
材料科学 材料科学基础
材料实验 材料合成与加工
复合材料 材料科学其他学

生产能力
机械装备制造业 切削加工 钳加工 压力加工 压力及离心铸造 离子束加工
磨料流加工 液体喷射加工 超声波加工 磨料喷射加工 电解加工 电铸和涂铸加工
整体机表面热处理工艺 砂型及熔模铸造 熔焊及钎焊 电子束加工 电火花加工
激光加工 等离子弧加工 化学热处理 化学铣切加工 照相制版加工 光刻加工
光电成形电镀 复合切削加工 超声放电加工 超声电解加工 电解电火花磨削
包装与装配 压焊 声能加工 光能加工 磁能加工 辐射加工 其他
电子元器件制造业 光绘工艺 钻孔工艺 孔金属化工艺 镀锡铅合金工艺
锡铅合金镀层的退除工艺 丝印阻焊剂工艺 热风整平工艺 机械成型工艺
加厚镀铜工艺 机加工 图形转换-光刻工艺 图形转换-刻蚀工艺 杂质参杂-扩散工艺
杂质参杂-离子注入工艺 退火-炉退火工艺 退火-快速退火工艺
制膜（二氧化硅制备）-氧化法 制膜（二氧化硅制备）-CVD
制膜（二氧化硅制备）-PVD 集成电路封装工艺 集成电路装配与测试 辅助工序
其他

MCs). The approach also tries to use IoT which can provide real-time information of manufacturing objects and activities, to enable a new dynamic service selection paradigm, which can narrow the gap between the decision and the actual service execution (affected by disturbances).

There are still many open issues to be solved in the integration of multiple MCs. In the FCM approach, semantic and SOA-based integration methods of different MR/Cs need to be further researched, by considering the types of MR/Cs. The leasing of manufacturing software is certainly different from that of hard resource, such as machine tools. Domain-specific demands and characteristics of business collaboration should also be considered to design efficient collaboration algorithms for any industry. For the TPCM approach, we will further research on a new dynamic service selection paradigm, which takes advantage of real-time information enabled by IoT. In today's highly dynamic business environments, various disruptions can occur and disrupt service executions. With IoT's pervasive ability to capture critical disruptions, abundant services from multiple MCs and event-driven service selection approaches should be adopted to address various uncertainties and optimally fulfill user tasks. Another important and common issue in the era of cloud and IoT is trust, security, and privacy. This paper does not consider such issue. More efforts should be made from both a legislative and technical point of view. Those aspects of our framework should also be further investigated and are left as our future work.

Reference

1. Armbrust M, Fox A, Griffith R, Joseph AD, Katz R, Konwinski A, Lee G, Patterson D, Rabkin A, Stoica I, Zaharia M (2010) A view of cloud computing. Commun ACM 53(4):50–58
2. Li BH, Zhang L, Wang SL, Tao F, Cao JW, Jiang XD, Song X, Chai XD (2010) Cloud manufacturing: a new service oriented networked manufacturing model. Comput Integr Manuf Syst 16(1):1–7
3. Xu X (2012) From cloud computing to cloud manufacturing. Robot Comput Integr Manuf 28(1):75–86
4. Tao F, Zhang L, Venkatesh V C, Luo Y, Cheng Y (2011) Cloud manufacturing: a computing and service-oriented manufacturing model. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture DOI: 10.1177/0954405411405575
5. Li BH, Zhang L, Ren L, Chai XD, Tao F, Luo YL, Wang YZ, Yin C, Huang G, Zhao XP (2011) Further discussion on cloud manufacturing. Comput Integr Manuf Syst 17(3):449–457
6. Huang B, Li C, Yin C, Zhao X (2013) Cloud manufacturing service platform for small-and medium-sized enterprises. Int J Adv Manuf Technol 65(9–12):1261–1272
7. He W, Xu L (2015) A state-of-the-art survey of cloud manufacturing. Int J Comput Integr Manuf 28(3):239–250
8. Valilai OF, Houshmand M (2013) A Collaborative and Integrated Platform to Support Distributed Manufacturing System Using a Service-Oriented Approach Based on Cloud Computing Paradigm. Robot Comput Integr Manuf 29(1):110–127
9. Kirkham T, Armstrong D, Djemame K, Jiang M (2014) Risk driven Smart Home resource management using cloud services. Futur Gener Comput Syst 38:13–22
10. Rochwerger B, Breitgand D, Levy E, Galis A, Nagin K, Llorente IM, Montero R, Wolfsthal Y, Elmroth E, Caceres J, Ben-Yehuda M, Emmerich W, Galan F (2009) The reservoir model and architecture for open federated cloud computing. IBM J Res Dev 53(4):1–11
11. Grozev N, Buyya R (2014) Inter-Cloud architectures and application brokering: taxonomy and survey. Software: Practice and Experience 44(3):369–390
12. Wang XV, Xu XW (2013) ICMS: a cloud-based manufacturing system. In: Li W, Mehnen J (eds) Cloud manufacturing. Springer-Verlag, London, pp 1–22
13. Lu Y, Xu X, Xu J (2014) Development of a hybrid manufacturing cloud. J Manuf Syst 33(4):551–566
14. Sun H, Fan W, Shen W, Xiao T (2012) Ontology-based interoperation model of collaborative product development. J Netw Comput Appl 35(1):132–144
15. Dahmann JS, Kuhl F, Weatherly R (1998) Standards for simulation: as simple as possible but not simpler the high level architecture for simulation. Simulation 71(6):378–387
16. Fan WH, Xiao TY (2011) Integrated architecture of cloud manufacturing based on federation mode. Comput Integr Manuf Syst 17(3):469–476
17. Elmroth E, Márquez FG, Henriksson D, Ferrera DP (2009) Accounting and billing for federated cloud infrastructures. Eighth International Conference on Grid and Cooperative Computing 2009:268–275
18. Toosi AN, Calheiros RN, Thulasiram RK, Buyya R (2011) Resource provisioning policies to increase IaaS provider's profit in a federated cloud environment. 13 rd International Conference on High Performance Computing and Communications (HPCC) pp 279–287
19. Lucas-Simarro JL, Moreno-Vozmediano R, Montero RS, Llorente IM (2013) Scheduling strategies for optimal service deployment across multiple clouds. Futur Gener Comput Syst 29(6):1431–1441
20. Montes JD, Zou M, Singh R, Tao S, Parashar M (2014) Data-driven workflows in multi-cloud marketplaces. 7th International Conference on Cloud Computing pp 168–175
21. Zhang L, Luo Y, Tao F, Li BH, Ren L, Zhang XS, Guo H, Cheng Y, Hu A, Liu Y (2014) Cloud manufacturing: a new manufacturing paradigm. Enterp Inf Syst 8(2):167–187
22. Wu D, Rosen DW, Schaefer D (2014) Cloud-based design and manufacturing: status and promise. In: Schaefer D (ed) Cloud-Based Design and Manufacturing (CBDM). Springer International Publishing, Switzerland, pp 1–24
23. Chang V, Wills G, De Roure D (2010) A review of cloud business models and sustainability. 3rd International Conference on Cloud Computing pp 43–50
24. Ren L, Zhang L, Wang L, Tao F, Chai XD (2014) Cloud manufacturing: key characteristics and applications. International Journal of Computer Integrated Manufacturing pp 1–15
25. Ren L, Zhang L, Zhang YB, Tao F, Luo YL (2011) Resource virtualization in cloud manufacturing. Comput Integr Manuf Syst 17(3):511–518
26. Barham P, Dragovic B, Fraser K, Hand S, Harris T, Ho A, Neugebauer R, Pratt I, Warfield A (2003) Xen and the Art of Virtualization. Proceedings of the 19th ACM Sympo-sium on Operating Systems Principles 37(5):164–177
27. ISO 10303–1: Industrial automation systems and integration – product data representation and exchange – Part 1: Overview and fundamental principles; 1994

28. Lenhart A, Madden M (2007) Social networking websites and teens: An overview. Pew/Internet
29. Wu D, Greer MJ, Rosen DW, Schaefer D (2013) Cloud manufacturing: strategic vision and state-of-the-art. J Manuf Syst 32(4):564–579
30. Chen H, Chiang RHL, Storey VC (2012) Business intelligence and analytics: from big data to big impact. MIS Q 36(4):1165–1188
31. Bi Z, Cochran D (2014) Big data analytics with applications. J Manag Analytics 1(4):249–265
32. Qu T, Lei SP, Wang ZZ, Nie DX, Chen X, Huang GQ (2015) IoT-based real-time production logistics synchronization system under smart cloud manufacturing. The International Journal of Advanced Manufacturing Technology pp 1–18
33. Huang V, Javed M K (2008) Semantic sensor information description and processing. The Second International Conference on Sensor Technologies and Applications pp 456–461
34. Wache H, Voegele T, Visser U, Stuckenschmidt H, Schuster G, Neumann H, Hubner S (2001) Ontology-based integration of information-a survey of existing approaches. Proceedings of IJCAI-01 workshop: ontologies and information sharing pp 108–117
35. Valipour MH, AmirZafari B, Maleki KN, Daneshpour N (2009) A brief survey of software architecture concepts and service oriented architecture. 2nd International Conference on Computer Science and Information Technology pp 34–38
36. Chu X, Buyya R (2007) Service oriented sensor web. Sensor networks and configuration. Springer, Berlin
37. Hribernik KA, Warden T, Thoben KD, Herzog O (2010) An internet of things for transport logistics–an approach to connecting the information and material flows in autonomous cooperating logistics processes. Proceedings of the 12th international MITIP conference on information technology & innovation processes of the enterprises pp 54–67