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ORIGINAL ARTICLE

CMfgIA: a cloud manufacturing application mode for industry alliance

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Abstract

Industry alliance is a cooperative mode based on some kind of contract or restraint, which is a new stage of the evolution and development of industrial cluster. In order to enhance the sharing ability of manufacturing resources, a new application mode called cloud manufacturing for industry alliance (CMfgIA) is presented in this paper. Firstly, the concept, architecture, and operation mechanism of CMfgIA is elaborated. Secondly, a domain-driven development approach for multi- granularity manufacturing services is proposed to ensure on-demand supply of manufacturing resources. In the approach, an improved feature model which contains process information of service composition is used to construct domain requirements. Based on the feature model, two-phase development process of manufacturing service is described. In the first phase, atomic manufacturing services are developed based on atomic features, and in the second phase, coarse-grained manufacturing services are modeled through automatic service composition which is realized by feature model customization. Then, a relationship management model is applied to manage the relationships between customized feature models and manufacturing services. Finally, an application example of cloud manufacturing platform for elevator industry alliance is given to verify the feasibility and effectiveness of CMfgIA.

Keywords Cloud manufacturing · Industry alliance · Multi-granularity manufacturing services · Domain requirements · Feature model

1 Introduction

In order to quickly respond to customer's diverse requirements, shorten product development cycle, reduce research costs, and maintain market agility, today's manufacturing enterprises are transforming and upgrading from production-oriented type to service-oriented and intelligence-oriented type [1, 2]. Cloud manufacturing [3–5, 50, 60], a new service-oriented manufacturing model, is proposed. It aims to satisfy diversified and personalized requirements of users, and truly allocate manufacturing resources on demand [6]. On-demand services supply and utilization is a core feature of cloud manufacturing that differentiates from other network-based manufacturing models.

Designing a suitable cloud manufacturing application mode is of great significance to the landing of cloud manufacturing. It cannot only define the application object of manufacturing service, application scope, service modeling method and resource utilization strategy, but also directly affect the effectiveness and practicality of cloud manufacturing platform. For different application objects and industries, several cloud manufacturing application modes were proposed in current researches. For example, cloud manufacturing for small- and medium-sized enterprises (SMEs) and cloud manufacturing for group enterprises [22], cloud manufacturing for regional economy [29], cloud manufacturing for specific industry [66], and so on. However, most of the researches on cloud manufacturing application mode only stay at a theoretical level or prototype system level, and few of cloud manufacturing platforms (http://www.casicloud.com) are actually used and generate industrial value.

Industry alliance is a cooperative mode based on some kind of contract or restraint, and it is a new stage of the evolution and development of industrial cluster [9]. Usually,

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members in industry alliance have similar manufacturing requirements. Industry alliance seeks for new product standards, product positioning, and product collaboration based on common product technologies, and promote the healthy development of industry [10]. It helps to optimize the industrial resources allocation and thus improve the competitiveness of enterprises. However, manufacturing resources in the industry alliance have the characteristics of inter-region, heterogeneity and complexity, resulting in difficulties in resource sharing which makes it difficult to really bring into play the value of industry alliance.

Fortunately, cloud manufacturing gives a more effective way to improve the overall manufacturing capability of industry alliance. On the one hand, cloud manufacturing can effectively integrate various advantage and reliable manufacturing resources of members in industry alliance and form a shared resource pool which can be centralized management in the platform. Then, through composition of these resources, alliance members can enhance their competitiveness. On the other hand, industry alliance provides resource and organizational basis for the application and implementation of cloud manufacturing. Therefore, industry alliance is taken as the application object of cloud manufacturing and a new cloud manufacturing application mode called CMfgIA is proposed in this paper.

The rest of the paper is structured as follows: Section 2 discusses the related researches on the application modes of cloud manufacturing, Section 3 introduces the concept, architecture and operation mechanism of CMfgIA, Section 4 presents the domain-driven development process of manufacturing services, Section 5 gives an application example of cloud manufacturing platform for elevator industry alliance and Section 6 concludes the paper.

2 Related works

Cloud manufacturing application mode is one of the key issues for the landing of cloud manufacturing. When developing a cloud manufacturing platform or system, a specific application mode should be considered [51]. Many scholars have conducted in-depth research in application mode and put forward some cloud manufacturing platforms with industry characteristics. For example, manufacturing equipment cloud manufacturing platform [11], mold industry cloud manufacturing platform [12, 13], automobile and motorcycle parts industry cloud manufacturing platform [14, 15], sintering industry cloud simulation platform [16], aerospace industry cloud manufacturing platform [17–20], polymer materials industry cloud manufacturing platform [21], cloud computing and internet of things-based cloud manufacturing service system(CCIoT-CMfg) [52], cloud manufacturing-based solution for additive manufacturing systems [53], service-oriented remanufacturing platform [54], cloud manufacturing-based platform for optimisation in distributed manufacturing enterprises [55], prototype system for intelligent perception and access of manufacturing resource [63], interoperable cloud-based manufacturing system(ICMS) [64], machining service platform [67], and so on. Generally, these cloud manufacturing platforms or systems can be categorized into four deployment modes: private manufacturing cloud, public manufacturing cloud, community manufacturing cloud and hybrid manufacturing cloud [7, 8].

For SMEs, public manufacturing cloud is a promising choice [22]. Ren et al. proposed a cloud manufacturing platform prototype(MfgCloud) which was a public manufacturing cloud for SMEs. It gave a cloud-to-ground solution for cloud manufacturing [65]. Yin et al. put forward a cloud manufacturing application mode for SMEs and studied the common key technologies and architecture of the platform [23]; on this basis, Huang et al. developed a prototype platform called SME-oriented cloud manufacturing service platform (SME-CMfgSP) [24]. In order to meet the urgent requirements for equipment resource sharing and remote maintenance, Li et al. proposed a cloud manufacturing service platform for machine tool equipment and its processing and operation [11]. In the automobile industry, most enterprises are small- and medium-sized, public manufacturing cloud can help them to improve production development capability. For this purpose, Yin et al. proposed a new product development cloud manufacturing service platform to rapidly, effectively and reliably utilize the decentralized manufacturing resources [14]. Song et al. studied three common engines, namely intelligent matching engine, transaction coordinating engine and credit evaluation engine of cloud manufacturing platform, and verified them in the automobile and motorcycle parts industry [15]. In other industrial domain, such as in the steel manufacturing industry, Xiong et al. proposed a cloud simulation platform for the sintering production process [16]. Qiu et al. proposed a cloud manufacturing service platform for the polymer industry [21]. Recently, public manufacturing cloud was also applied in 3D printing industry. For consumers, they can enjoy a variety of customized products and even design and make their own products in the cloud; for producers, they can create on-demand products and thus save costs [25].

Different from the public manufacturing cloud, private manufacturing cloud is more suitable for large group enterprises [22, 49]. For example, enterprises in the aerospace industry are generally in large size. Because of the problems of low resource utilization rate and difficulties in controlling the group, private cloud manufacturing was applied [17, 18]. Lin et al. elaborated on five service modes for aerospace group enterprises, including job batch service mode, virtual interaction service mode, business process collaboration based on shared model service mode, space-time co-operation based on concurrent inter-operation service mode and capacity-oriented scheduling and collaboration service mode [20]. Another problem in group enterprises is redundant construction of manufacturing resource and capability. Zhan et al. talked about the cloud manufacturing application mode in China northern locomotive rolling stock industry (CNR) [26]. In other research, Kang et al. proposed a platform framework for group enterprises incorporating the thought of cellular manufacturing [27]. Li et al. explored the application mode of knowledge services for cloud manufacturing of group enterprises from the service perspective, built the system structure of knowledge service system and proposed static knowledge service and dynamic knowledge service [28].

Community manufacturing cloud often has distinctive regional and industrial characteristics. Wang et al. proposed a cloud manufacturing service platform for regional economies in which large group enterprises played a center role to improve the production level of regional manufacturing [29]. Usually, industrial cluster is a promising mode for organizing regional manufacturing resource. As the mold industry was regional, Li et al. proposed a cloud manufacturing platform for mold industrial cluster [13]. In order to fulfill the real-time designing and manufacturing information interaction among the collaborative partners in an industrial cluster area, Liu et al. designed an industrial-cluster-oriented cloud manufacturing service system (CMSS) for SMEs [30].

Hybrid manufacturing cloud is composed of two or more manufacturing clouds mentioned above, for example, integrating public manufacturing cloud and private manufacturing cloud [19, 31]. However, different manufacturing clouds may be not compatible, and federal model could be a possible solution [32, 33]. Tai et al. proposed a cloud manufacturing cooperation model based on enterprise supply and demand network, and formed a temporary virtual private cloud through the cooperation between enterprises, when the cooperation relationship ended and the resources were released to the public cloud platform [34]. Chen et al. proposed a hybrid cloud manufacturing platform for cutting tools recommendation. In the platform, private manufacturing cloud is used for the data safety and public manufacturing cloud is used computation scalability [35]. Yang et al. proposed a hybrid integration framework for integrating multiple manufacturing clouds to address the shortcomings of lacking of resources provided by a single platform [36]. Lu et al. suggested a hybrid manufacturing cloud to meet different needs of enterprises at different times [37]. Aleksic introduced a hybrid manufacturing cloud in the small or medium-sized enterprise one-of-a-kind production (SME OKP), which was realized on the Amazon Virtual Private Cloud (VPC) to connect the manufacturing local-area network with the Amazon VPC in the Amazon web service (AWS) cloud [38].

However, the existing researches are limited in solving practical requirements of industry alliance. The main reasons are as follows:

First, both private manufacturing cloud and public manufacturing cloud are not suitable for industry alliance. As private manufacturing cloud is mainly used in a large-scale enterprise or group, the manufacturing services are shared within the enterprise or group. However, the property rights of members in industry alliance are independent. Adopting private manufacturing cloud will lead to over-sharing of manufacturing resources and manufacturing capacity, which is detrimental to the protection of dominant enterprises. In contrast, manufacturing services in public cloud can be accessed by the registered users. The public manufacturing cloud tends to evolve into a platform for generic services. It is difficult to integrate reliable, sophisticated and personalized manufacturing services. As a result, it cannot effectively meet the requirements of industry alliance. Essentially, cloud manufacturing platform for industry alliance can be deployed as a contract-based community manufacturing cloud. Moreover, compared with the traditional industrial cluster, industry alliance can break through the geographical restrictions and achieve a wider range of resource sharing.

Second, current researches are mainly focused on technologies for virtualization and encapsulation of manufacturing resources or capabilities [39–41, 56–59]. However, the issue that what kind of services need to be encapsulated in the cloud manufacturing platform is lacked of thorough thinking [42]. That is to say, when developing manufacturing services, the requirements of users should be considered sufficiently. Otherwise, it may lead to the incompleteness of manufacturing resources or the waste of manufacturing resources in the platform. For service users, they may not be efficiently access to the required manufacturing resources. For service providers, they may encapsulate useless manufacturing services in the platform.

3 Concept, architecture, and operation mechanism of CMfgIA

3.1 Concept of CMfgIA

According to the characteristics of industry alliance, the concept of CMfgIA is proposed. The CMfgIA is defined as follows:

Definition 1(CMfgIA). CMfgIA is a cloud manufacturing application mode for industry alliance. It serves the members and improves the manufacturing level of industry alliance by providing common manufacturing services and personalized manufacturing services on demand.

The goal of the CMfgIA is to create a cloud platform for manufacturing service publish, access, composition, and execution based on the domain requirements of industry alliance. Figure 1 shows the conceptual model of CMfgIA.

The main roles of CMfgIA can be summarized into the following four types:

(1) Cloud manufacturing platform operator: The cloud manufacturing platform operator is responsible for verifying the authenticity and effectiveness of manufacturing services as well as dynamically managing and scheduling them to ensure the effective use of manufacturing resources.
(2) Manufacturing service provider: The manufacturing service provider is the alliance member that provide manufacturing resource. They encapsulate competitive manufacturing resources into manufacturing services, and publish them in the cloud manufacturing platform after approved by the cloud manufacturing platform operator. Based on the utilization of manufacturing services, the manufacturing service provider can obtain corresponding benefits.
(3) Manufacturing service user: The manufacturing service user is the alliance member with manufacturing requirements. They should pay for the use of common manufacturing services or personalized manufacturing services in the platform.
(4) Industry alliance organizer: The industry alliance organizer is responsible for supervising and guiding the members of industry alliance, including organizing alliances to set industry standards, issuing alliance agreements and providing industry regulations and policies to ensure the normal operation of industry alliance.

It should be pointed out that the members in the alliance can be one or more of the above roles. For example, special equipment testing institute in the elevator industry alliance is not only the organizer that supervises the industry alliance, but also the provider that provides testing services. Therefore, the roles of alliance members are multidimensional.

3.2 Architecture of CMfgIA

The core architecture of CMfgIA includes five layers: manufacturing resource layer, manufacturing service layer, manufacturing service engine layer, domain requirements management layer, user layer as well as the corresponding environment used to support the operation of CMfgIA. The architecture is shown in Fig. 2.

(1) Manufacturing resource layer: This layer covers the physical manufacturing resources distributed in different geographical locations involved in the lifecycle of product design and development. There are five types of manufacturing resources: hardware resources, software resources, knowledge resources, part resources and human resources, which can be accessed by virtualization and encapsulation through the CMfgIA.
(2) Manufacturing service layer: This layer mainly covers seven categories of manufacturing services: design and calculation services, analysis services, standard part selection services, non-standard part processing services, assembly services, and type testing services. These manufacturing services include common manufacturing services and personalized manufacturing services. For example, in the design and calculation services, the tractor design of elevator belongs to the common design service, while the load-bearing beam calculation service belongs to the personalized design service. The type test service is common manufacturing services, because each developed product needs to be tested.
(3) Manufacturing service engine layer: This layer is mainly used for manufacturing service management, including three main engines: manufacturing service modeling engine, manufacturing service management engine, and manufacturing service composition engine. Manufacturing service modeling engine is used to model manufacturing services, including service registration, service description, and service test. Manufacturing service management engine is used to dynamically manage manufacturing services, including services adding, services deleting, services modifying, services querying, dynamic QoS management, service evaluation, and service evolution management; manufacturing service composition engine is used for dynamic composition and execution of services to meet the complex requirements of alliance members.
(4) Domain requirements management layer: This layer is used for the management of the feature models which present the domain requirements at different granularities. It mainly includes product design feature model, processing, and assembly feature model, and product testing feature model.
(5) User layer: This layer provides a unified, efficient and secure UI interface for the members in industry alliance. Through the interface, manufacturing services can be conveniently published, used and managed.

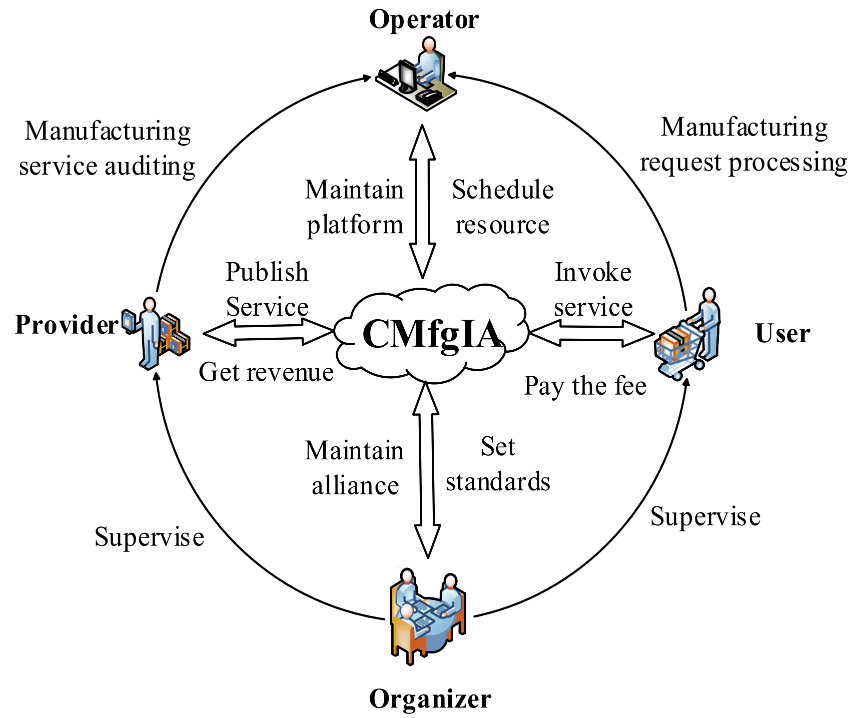


Fig. 1 Conceptual model of CMfgIA

The above five layers are the core functions of CMfgIA. To support the operation of CMfgIA, the corresponding supportive environment needs to be configured, including the operating environment and the operation rules of the industry alliance.

3.3 Operation mechanism of CMfgIA

The operation mechanism of CMfgIA is shown in Fig. 3.

Firstly, enterprises need to pass the certification of the industry alliance organizer and then become a member (provider or user) of the industry alliance. They should finish the registration and obtain the right to use or publish manufacturing services.

Secondly, the manufacturing service providers submits the servitization request of manufacturing resource. Then, the competitive resources of manufacturing service providers are encapsulated into manufacturing service through the manufacturing service modeling engine.

Thirdly, the manufacturing service users publish personalized manufacturing requirements, which are transformed into composition demand through the domain requirements model. Based on the composition demand, the service composition engine will give a suitable service composition instance (a new one or an existing case).

Then, the service composition instance needs to be executed. In order to ensure the reliability of the execution of service composition, the manufacturing service management engine obtains the dynamic information of manufacturing services in real time. The execution of the service composition can be adjusted automatically according to the feedback information and thus to improve the self-adaptive ability.

Finally, the manufacturing resource is released if the service composition instance has been executed.

4 Domain-driven development process of manufacturing service

To ensure the value of manufacturing resources and avoid the servitization of useless resources, manufacturing services development in industry alliance should be based on user's requirements. In the industry alliance, due to the cohesion and stability of the domain knowledge, the user's manufacturing business requirements often have some common features and do not change greatly in a period of time. Therefore, these common business requirements have reusable value. In order to guide the alliance members to develop manufacturing services in a targeted manner, the primary task is to extract and manage common requirements and personalized requirements within the alliance, and to build a relatively complete domain requirements model.

Domain engineering is a popular approach to construct similar systems or products with common requirements, and it covers all the activities to establish reusable resources [43]. Therefore, it is used to guide the development of manufacturing services for CMfgIA. Figure 4 shows the domain-driven development process of manufacturing service for CMfgIA.

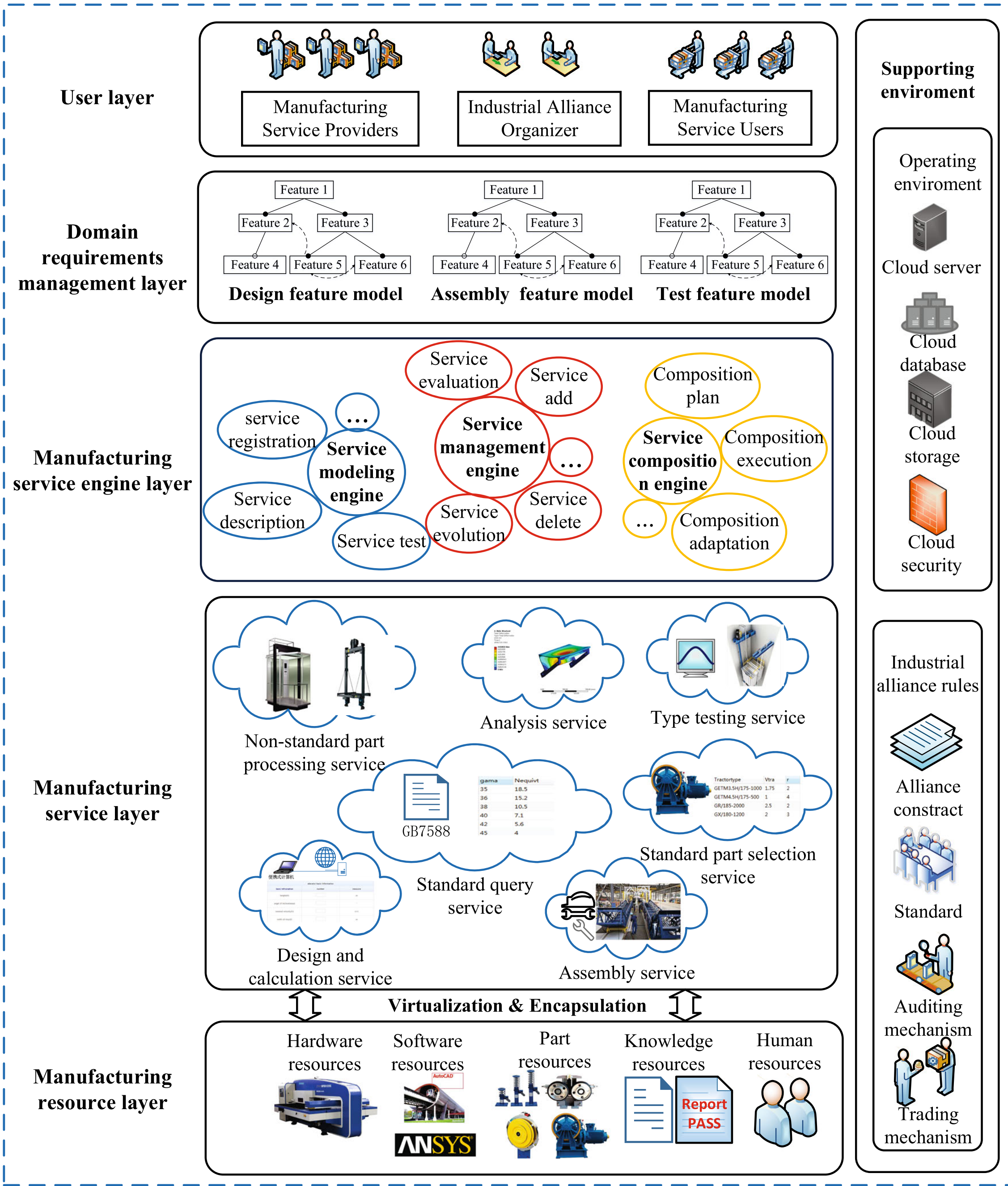


Fig. 2 Architecture of CMfgIA

From the perspective of domain engineering, the whole process includes domain analysis, domain design and domain implementation. From the perspective of manufacturing service development, the whole process contains service analysis, service extraction and service modeling. The output of the domain engineering stage is the input of the manufacturing service development stage. And driven by the evolution of requirements, the modeling process of manufacturing services become a closed-loop circulation system. Thus, core assets (e.g., manufacturing service library, domain requirement model.) can be dynamically adjusted according to the change of manufacturing requirements and better support the manufacturing activities in industry alliance. Then, the core assets are used in the service composition to meet complicated manufacturing requirements. The service composition instance can also be stored into the manufacturing service library and become a kind of reusable assets.

The reusable core assets obtained mainly include domain requirements model and manufacturing service library. The

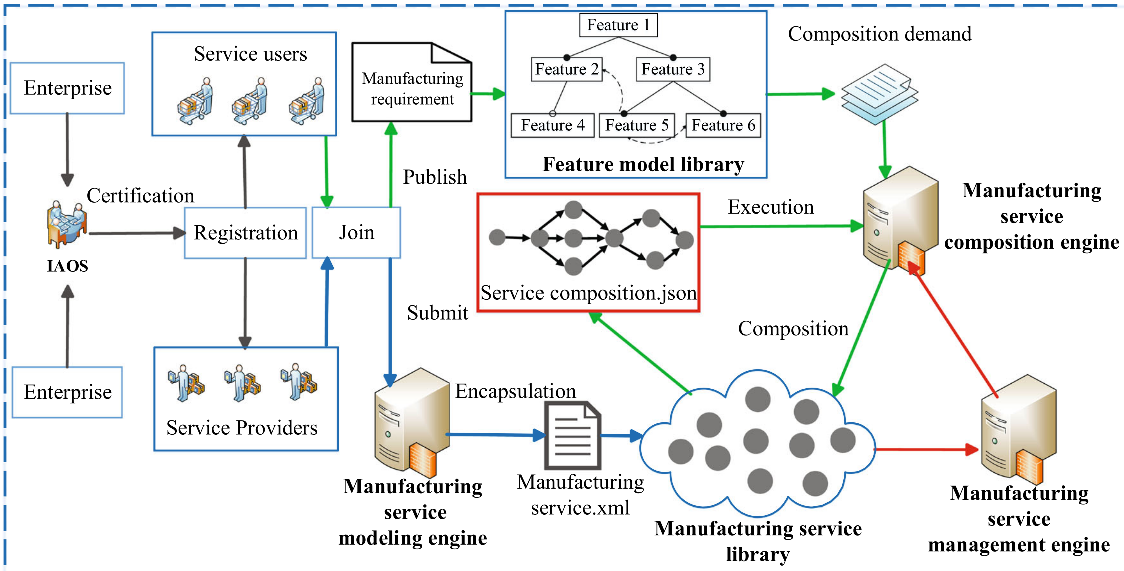


Fig. 3 Operation mechanism of CMfgIA

former describes the required manufacturing resources from the service users' perspective, and the latter describes the servitization of manufacturing resources from service providers' perspective.

4.1 Domain requirements model

The domain requirements model is the product of the domain engineering. It is the description model of requirements summarized by the domain experts and has guiding significance for the development of manufacturing services. When constructing the domain requirements model for CMfgIA, the following aspects should be considered.

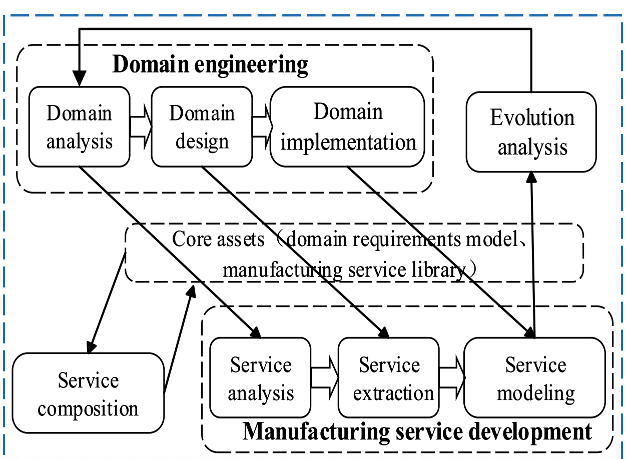


Fig. 4 Domain-driven development process of manufacturing service

First, the completeness of manufacturing business requirements: both common requirements and personalized requirements should be considered in the domain requirements model. And it can be better to guide the modeling of manufacturing services and to build a relatively complete manufacturing service library.

Second, the multi-granularity characteristic of manufacturing business requirements: the manufacturing requirements in the industry alliance are multi-granularity. For example, during the design process of elevator, the multi-granularity of user's design requirements can be atomic design requirements (e.g., motor power calculation), part design requirements (e.g., motor design verification), system design requirements (e.g., traction system design), and product design requirements (e.g., elevator design). Therefore, building multi-granularity domain requirements models is beneficial to manage requirements from different levels.

Third, the evolution of manufacturing business requirements: new requirements, new standards, new materials, and new technologies will affect the manufacturing of the product, so new manufacturing services need to be modeled or evolved to handle these changes to keep the advancement and validity of manufacturing services.

Fourth, the dependency relationship of business activities: manufacturing business activities refer to the manufacturing process that needed to accomplish for specific goals, for example, the design of the bending torque of guide rail (a component of elevator) is a design business activity. Business logic dependency relationship always exists between business activities. That is, the output of one manufacturing activity may be the input of another manufacturing activity.

The dependency relationship is the basis of manufacturing service composition.

Feature-oriented modeling approach is often used to construct domain requirements model. For example, features were originally used to model reusable components in software product lines or software product family [44]. In recent years, feature models have been applied to establish business process family, which can express the commonality and variability of business process [45, 46]. Feature provides a basic unit for modeling and managing reusable components in the domain. And using a feature-oriented approach to construct domain requirements model facilitates a straightforward and intuitive description of user manufacturing business requirements and their relationships. Therefore, in this paper, feature-oriented modeling approach is adopted to construct the domain requirements model. According to the approach, the manufacturing business activities and their dependency relationships are extracted and abstracted as features and the relationships of features in a feature model to express the common requirements and personalized requirements.

In order to facilitate the elaboration, a brief introduction of related concepts are shown as follows [47]:

Root feature: For each feature model, there is only one root feature. In general, the name of the root feature is the same as the name of the current domain, and the root feature is always in the bound state. For example, elevator design is the root feature for elevator design feature model.

Atomic feature: It represents a feature that is abstracted from the manufacturing activity with smallest granularity.

Relationship of features: Relationship of features can be summarized into two categories: refined relationship and constraint relationship. The refined relationship is used to represent a binary relationship between father feature and its sub-features. The refined relationship can be divided into mandatory feature and optional feature. And these features with different granularities are organized as a tree structure. Constraint relationship describes the binding relationship between the binding states of a feature. Constraint relationship includes the dependency relationship and exclude relationship between two features, as well as the XOR relationship and OR relationship between father feature and its sub-features.

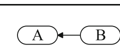
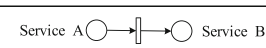
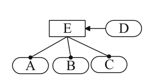
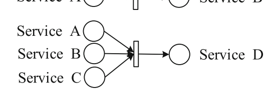
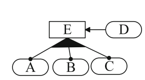
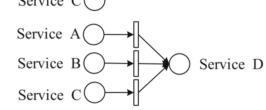
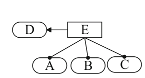
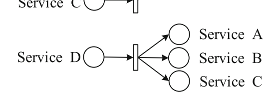
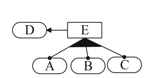
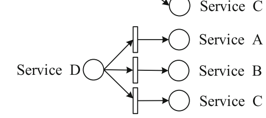
According to the approach, the manufacturing business activities and their dependency relationships are abstracted as features and the relationships of features in a feature model to express the common requirements and personalized requirements. However, when the feature model is used in service composition, an extra business process model needs to be provided as a composition template [46]. In other words, the feature model and business process model are constructed separately. The resulting feature model do not include the process information used for manufacturing service composition. Without the direct mapping relationship between the feature model and the service composition instance, the reuse of business process information and service composition instance is difficult. For this reason, new feature relationships need to be introduced to express the dependence of manufacturing services and modify the traditional feature model. In our previous research, five kinds of service composition relationships were defined. They were sequential dependence, concurrent dependence, selective dependence, merged dependence, and synchronous dependence [48]. Conversion rules between service composition process and feature relationship are as shown in Table 1.

According to the above concepts and rules, the domain requirements model for industry alliance can be constructed in the following step.

Step1: According to the different phases of product development, the domain experts extract the features of manufacturing business activities and the relationships between these features to construct product-level feature model, including product design feature model, product sample processing feature model, and product testing feature model.

This process involves rich domain knowledge. When constructing a domain requirements model (i.e., feature model), domain experts firstly should build users' manufacturing business process requirements set as the original input information. These original input information can be obtained mainly from the existing manufacturing business systems, manufacturing business process documents, manufacturing standard documents, and so on from the members of industry alliance. Actually, the original input information

Table 1 Conversion rules between service composition process and feature relationship

Index	Feature Relationship	Service composition process
1		
2		
3		
4		
5		

is needed to be standardized by preprocessing. For example, when constructing an elevator design feature model, the data noise mainly comes from the differences in the granularity of manufacturing business activities and manufacturing business activity terms (e.g., motor power calculation and tractor power calculation represent the same business activity). The standard manufacturing business process can be obtained by domain dictionary which refer to the collection of terms or expressions in a specific area [61]. Finally, the obtained standard manufacturing business process should be abstracted into manufacturing business features and their dependencies as the basis for the construction of feature model.

Step2: Domain experts decompose the constructed product-level feature model into feature models with different granularities, such as system-level feature models, unit-level feature models, and atom-level feature models.

Step3: The feature models of different granularities constitute a feature model library to facilitate the granular management of domain requirements. More importantly, it also enables rapid access to manufacturing service composition instances.

Figure 5 gives an example of feature models about elevator design. As shown in the Fig. 5a, it is an elevator design feature model. The features are organized as a tree.

There are two kinds of features: father feature and atomic feature. For example, traction system design is a father feature which can be divided into several sub-features. Moreover, the elevator design is a special father feature called root feature. Atomic features includes the tractor parameter query, power calculation, and torque verification.

There are three categories of feature relationships: refined relationship, constraint relationship, and process dependency relationship.

First, the refined relationship consists of mandatory and optional relationship. For example, the traction system design is a mandatory feature. When its father feature (elevator design) is bound, it must be chosen. The tension device design is an optional feature. When its father feature (balance system design) is bound, it can be chosen or not chosen.

Second, the constraint relationship consists of OR, XOR, Require, and Exclude relationship. For example, the OR relationship can be seen between traction force design and its sub-features. The braking condition (lowest) and braking condition (highest) should be chosen at least one when the traction force design is bound. The XOR relationship can be seen between traction force (counterweight side) and its sub-features. If it is bound, only one of its sub-features can be chosen. The Require relationship can be seen between tension device design and traction force calculation (with compensation device and tension device). The tension device design is required to be chosen when the traction force calculation (with compensation device and tension device) is bound. The Exclude relationship can be seen between tension device design and compensation chain choose. If the tension device design is bound, the compensation chain choose is forbidden to choose and vice verse.

Third, the process dependency relationship of service composition exits between an atomic feature and another feature (an atomic feature or a father feature). For example, it is a sequential dependency relationship (index 1 in Table 1) between tractor parameter query and tractor type choose. Moreover, a concurrent dependency relationship (index 2 in Table 1) can be seen among torque verification, max torque calculation and working torque calculation.

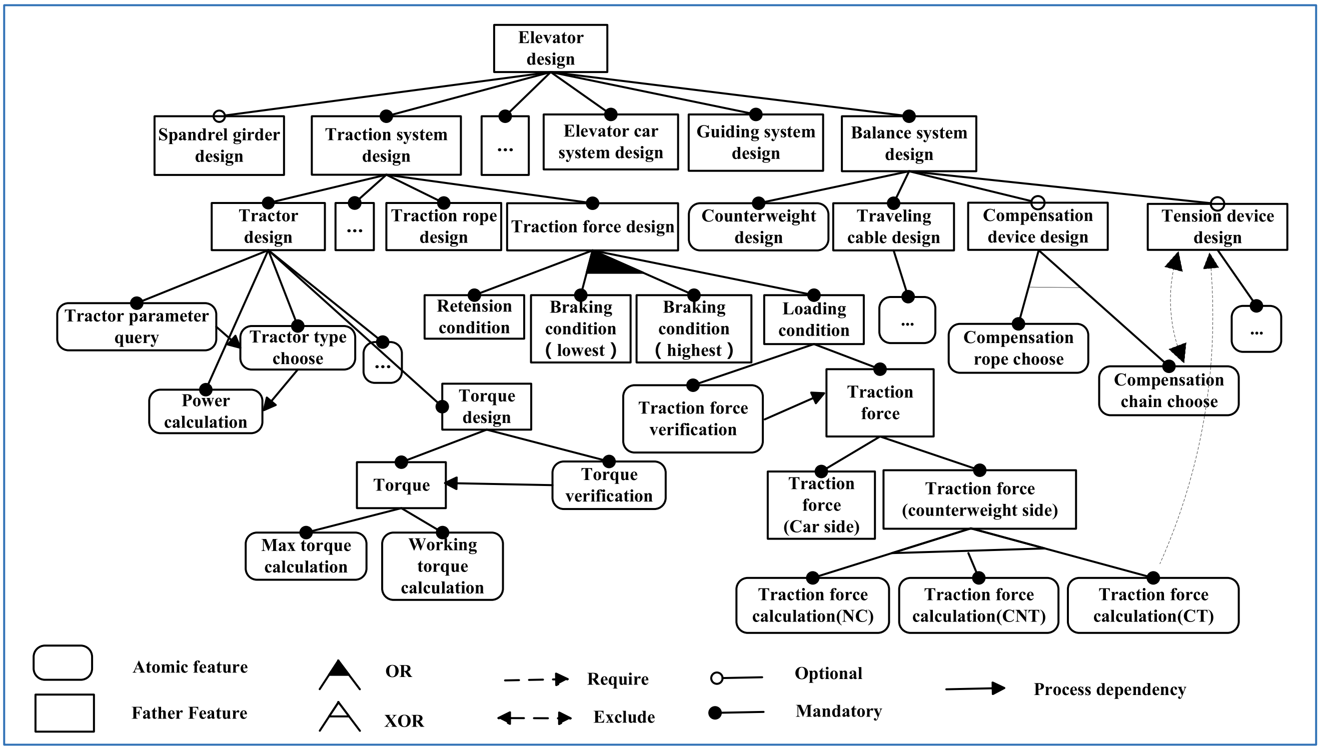
Actually, the elevator design feature model is a product-level feature model. It can be decomposed into feature models with different granularities, such as traction system feature model, balance system design feature model, and traction force design feature model. Figure 5b shows the balance system design feature model which is a system-level feature model. Besides, Fig. 5c shows a customized balance system design feature model. It is obtained from the balance system design feature model (as shown in Fig. 5) by deleting some features and relationships. It can be used in service composition and satisfy specific requirements of users.

4.2 Multi-granularity manufacturing service

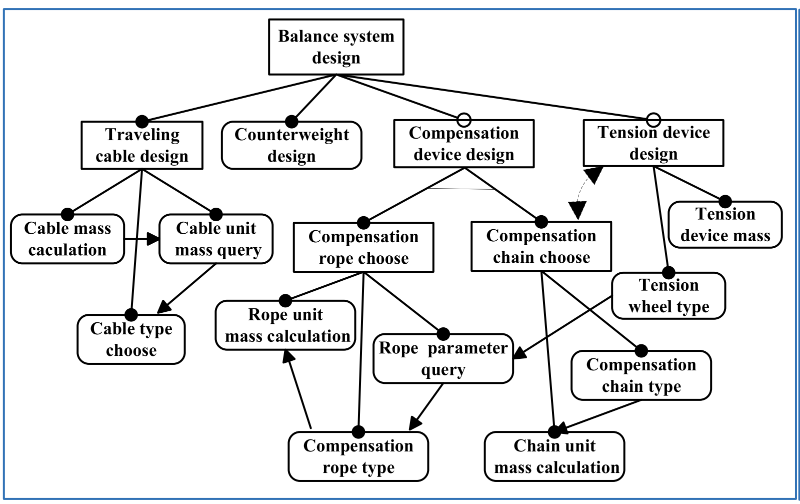
The feature model describes the common requirements and the personalized requirements in the industry alliance from the user's perspective. It models the requirements of different phases and different granularities in the product development process completely. The manufacturing services developed under the guidance of feature model have strong systematicness, cohesion, and reusability, and can better support the manufacturing activities of the alliance members.

Corresponding to the multi-granularity requirements, the manufacturing service can be divided into four types, including atom-level manufacturing service, unit-level manufacturing service, system-level manufacturing service and product-level manufacturing service. Manufacturing services with different granularities are defined as follows:

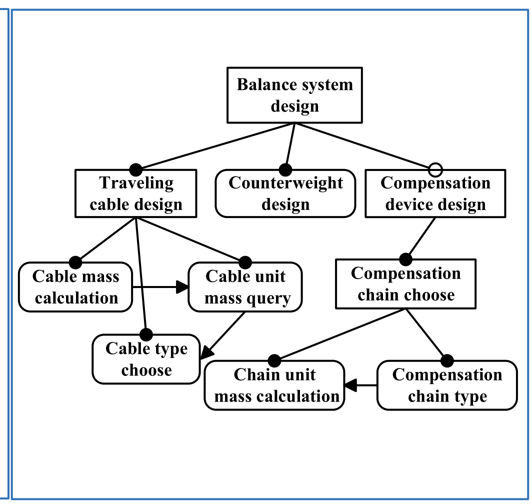
1) Atom-level manufacturing service. The atom-level manufacturing service is non-dividable and has the smallest granularity. For example, the bending torque design service of elevator design.



(a) Elevator design feature model



(b) Balance system design feature model



(c) A customized feature model

Fig. 5 Feature models about elevator design

2) Unit-level manufacturing service. The unit-level manufacturing service is composed of several atom-level manufacturing services and can be used to finish part manufacturing. For example, the guide rail design service of elevator design.
3) System-level manufacturing service. The system-level manufacturing services is composed of several unit-level manufacturing services and can be used to finish system manufacturing. For example, the traction system design service of elevator design.
4) Product-level manufacturing service. The product-level manufacturing service has the largest granularity and can be used to finish the product manufacturing. For example, the elevator design service.

In order to illustrate the progressive relationship of manufacturing services at different levels, an example about elevator design is given in Table 2. As shown in Table 2, the elevator design service is a product-level service, it is composed of several system-level services such as traction

Table 2 Progressive relationship of manufacturing services at different levels

Service level	Service name	Components
Product-level	Elevator design	Traction system design
		Balance system design
		Elevator car system design
		......
System-level	Traction system design	Tractor design
		Traction force design
		Traction rope design
		......
Unit-level	Tractor design	Tractor power calculation
		Tractor type choose
		Tractor parameter query
		......
Atom-level	Tractor power calculation	
	Tractor type choose	
	Tractor parameter query	
	......	

system design service, balance system design service, and elevator car design service. The traction system design service is a system-level service which consists of tractor design service, traction force design service, traction rope design service, and so on. The tractor design service is a unit-level service. It is composed of atom-level services which are tractor power calculation service, tractor type choose service, tractor parameter query service, and so on.

4.2.1 Phase 1: atomic manufacturing service development

The first phase of manufacturing service development is to model atomic manufacturing services. After constructing the feature model, the atomic features can be extracted. These atomic features express the domain requirements with smallest granularity. Then, the service providers encapsulate manufacturing resources into atomic services based on atomic feature. For example, tractor parameter query is an atomic feature as shown in Fig. 5a. Many tractor providers in the industry alliance can publish tractor parameter query services for the alliance members.

In order to realize the service composition automatically in phase 2, a registration template is provided for manufacturing service providers to publish standardized manufacturing services. And the mapping relationship between atomic manufacturing business feature and atom-level manufacturing service is established through the registration template. Along with the increasing number of services, the atom-level manufacturing service library with a certain scale is formed.

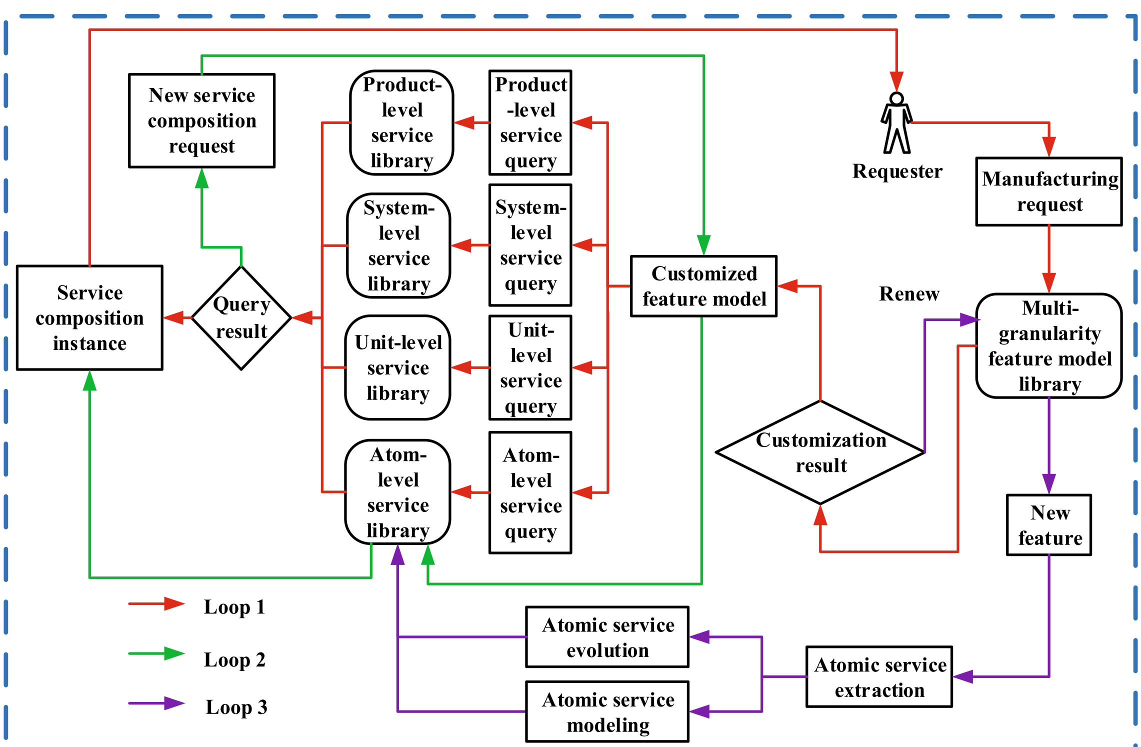


Fig. 6 Manufacturing service composition process

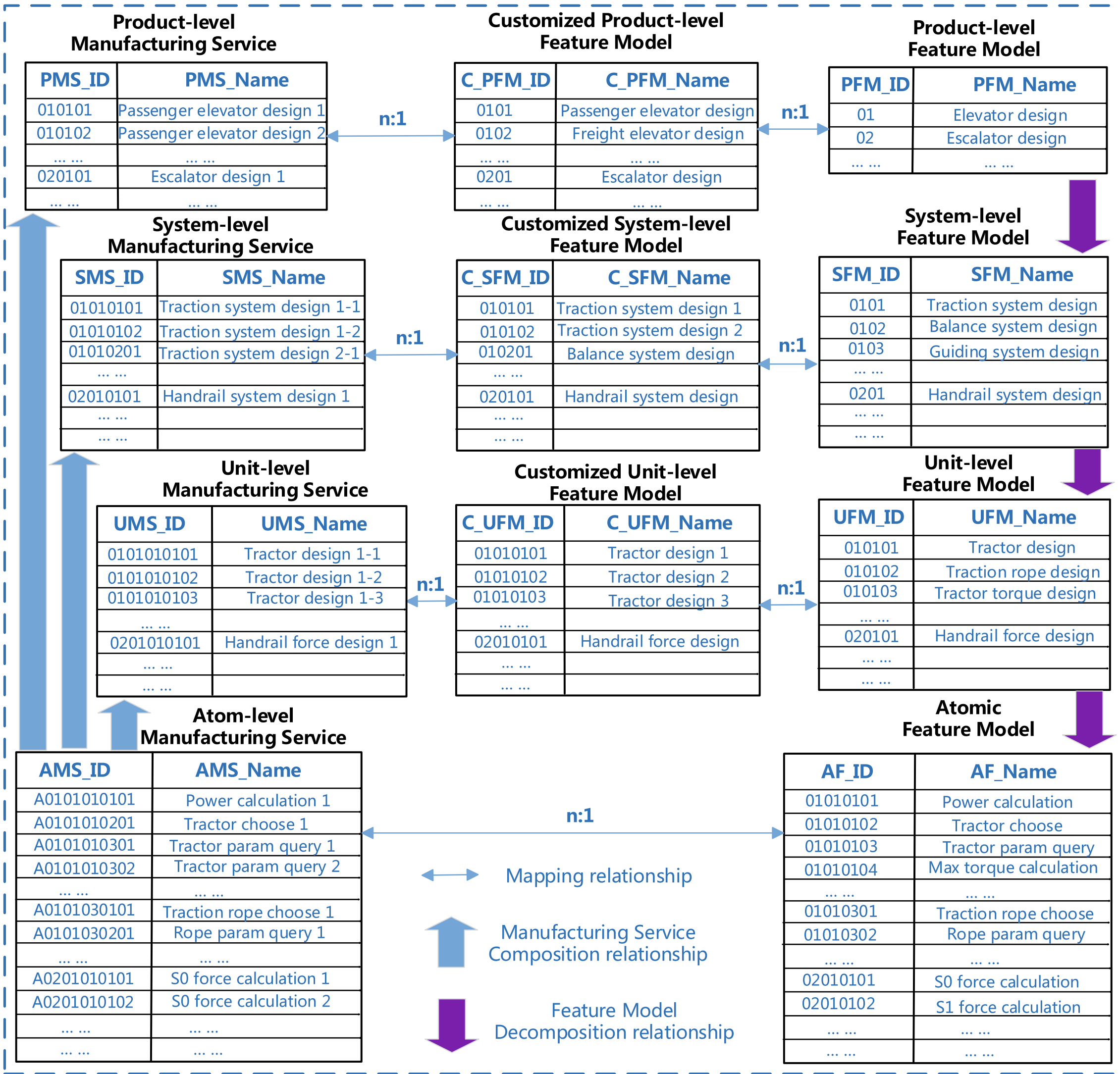


Fig. 7 Relationship management model

4.2.2 Phase 2: coarse-grained manufacturing service development

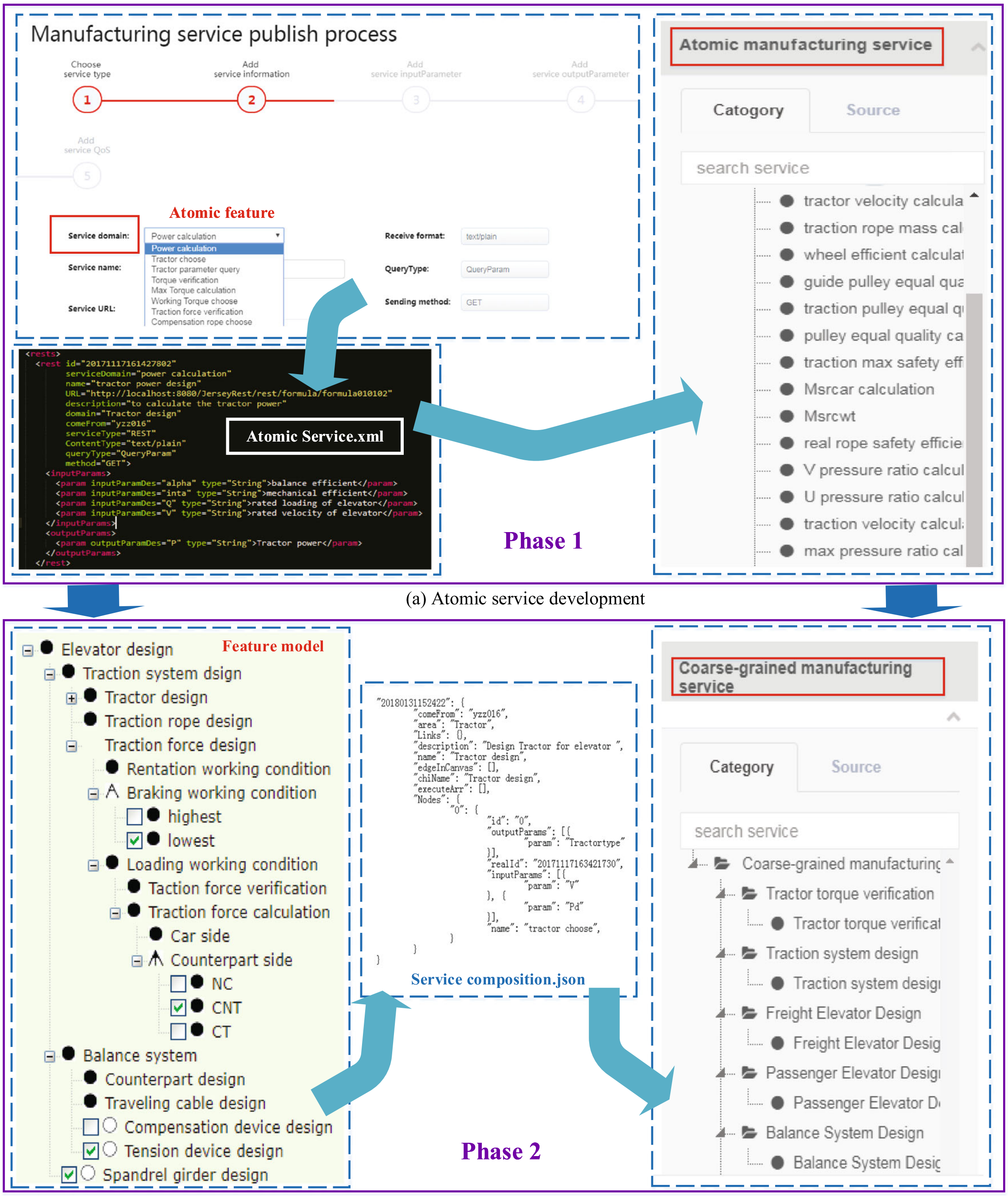
Atomic manufacturing services only have simple functions, while complex manufacturing requirements often need coarse-grained manufacturing services through service composition [62]. The entire manufacturing service composition process is described in Fig. 6. It consists of three closed-loops.

The first closed-loop consists of loop1. The user's manufacturing requirements are transformed to a customized feature model. Then, an existing manufacturing service composition instance is provided by querying the corresponding manufacturing service library. For example, customized balance system design feature model in Fig. 5c is a system-level feature model. Therefore, the service composition engine will search the system-level service library to find a solution.

The second closed-loop consists of loop1 and loop2. If loop1 cannot give a manufacturing service composition instance, it enters into loop2. Based on the customized feature model, the service composition engine will schedule the atom-level manufacturing services in the library and give a service composition instance automatically.

The third closed-loop consists of loop1, loop2, and loop3. If loop1 cannot get a customized feature model, it enters into loop3. In this case, new features and relationships should be added in the feature model. Based on the new feature model, new atom-level manufacturing services can be modeled or evolved. After that, it enters into loop2. Through the composition of atom-level manufacturing services, executable service composition instance can be obtained.

In reality, at the early stage of cloud platform operation, the service composition instance is mainly obtained through the third closed-loop. The feature model may be



(b) Coarse-grained manufacturing service development

Fig. 8 Two-phase development process of manufacturing services

imperfect at this stage, which leads to the incompleteness of atom-level service library. Thus, the required service composition may not exist. The third closed-loop is a high-cost and long-cycle process. In the medium term, the service composition instance is mainly obtained through the second closed-loop. The atom-level service library is relatively perfect, but the unit-level service library, system-level service library, and product-level service library have not yet been established, and the reusable service composition instance is rare. In the mature period, as more and more coarse-grained manufacturing services being stored in the manufacturing service library, the first closed-loop becomes most frequently used method to get service composition instance. It greatly improves the efficiency of service matching process. Multi-granularity manufacturing service library has been basically formed. In short, the reusable assets obtained

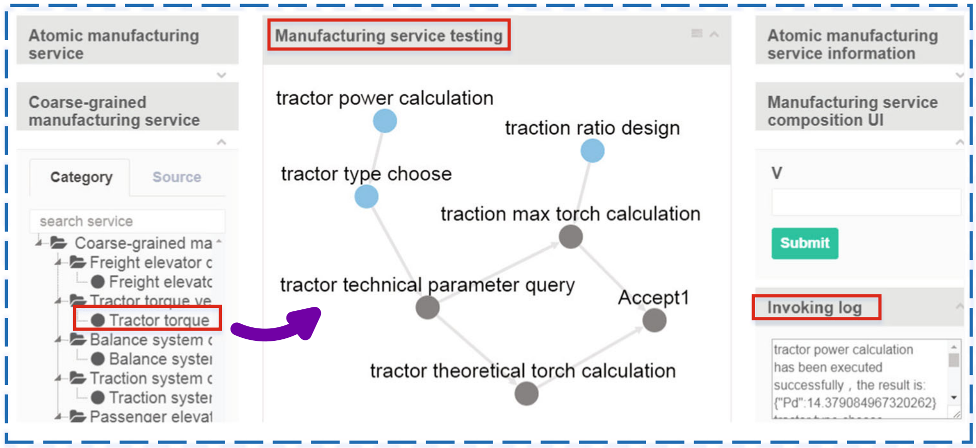


Fig. 9 Testing process of manufacturing service

in phase 2 are mainly coarse-grained manufacturing services.

4.3 Relationship management model

The relationship management model is introduced to manage the mapping relationships between feature models and service composition instances, the composition relationship of multi-granularity manufacturing services and the decomposition relationships of muti-granularity feature models. The relationship management model is shown in Fig. 7.

Firstly, mapping relationships between atomic features and atomic manufacturing services are constructed. When the manufacturing service registration is completed, the mapping relationship is automatically generated. Since an atomic feature can be bound to multiple atomic manufacturing services, it is a one-to-many relationship. For example, the tractor parameter query (in Fig. 5) is an atomic feature. The corresponding atomic manufacturing service can be called tractor technical parameters query service. Actually, there are many suppliers in industry alliance that can provide the service instance with the same function.

Secondly, during the process of service composition, a customized feature model is obtained by tailoring the domain requirements model. It is also a one-to-many relationship. For example, the passenger elevator design feature model and freight elevator design feature model can be customized from the elevator design feature model.

Thirdly, from a customized feature model, executable service composition instance can be directly obtained. As there may be several solutions, the relationship type is one-to-many.

Finally, the composition relationship of manufacturing services and the decomposition relationship of feature models are used to manage the services and feature models with different granularities.

5 Validation of CMfgIA

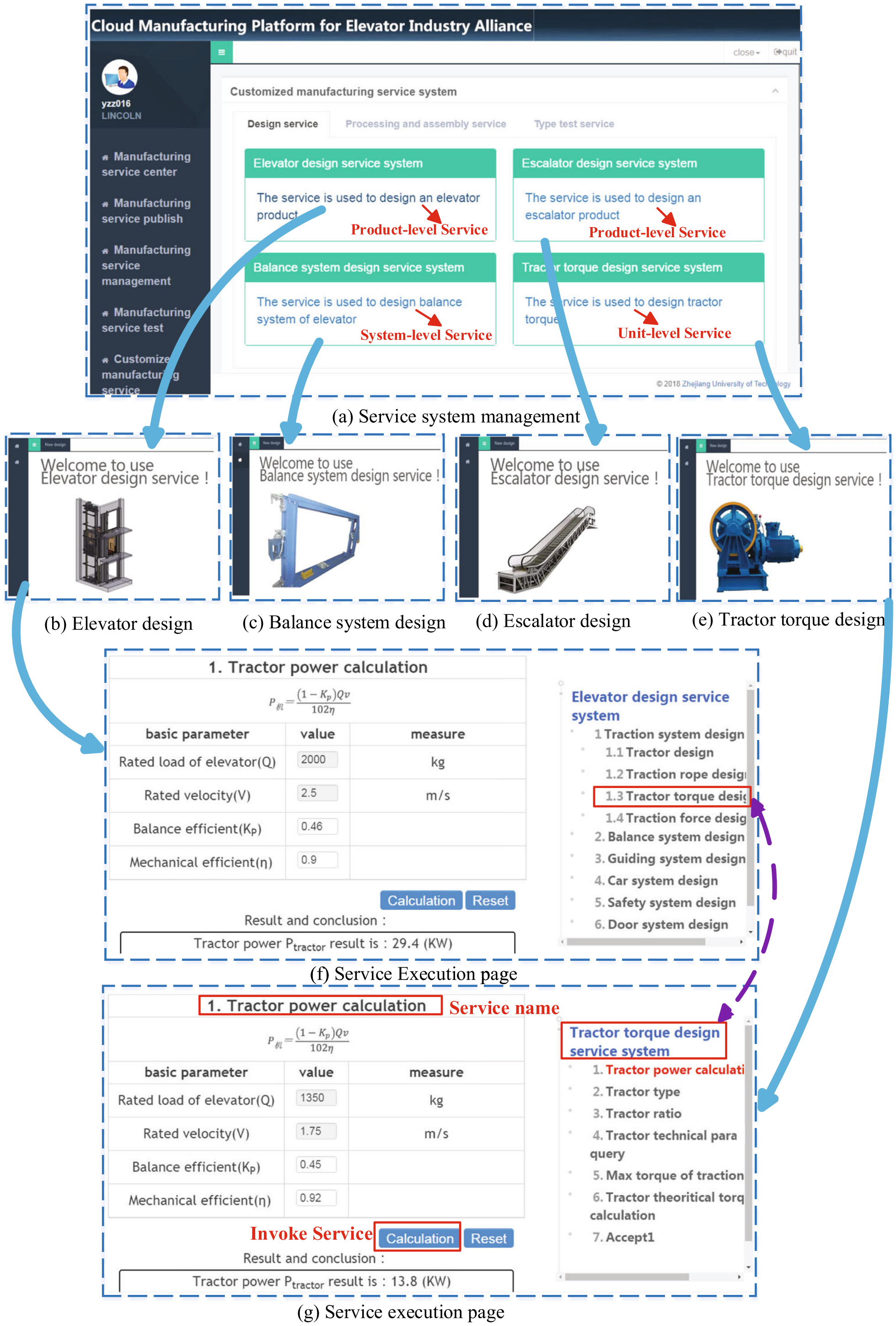
In order to verify the feasibility and effectiveness of CMfgIA, the authors' group have developed a cloud manufacturing service platform for the elevator industry alliance. It can be used to promote the effective integration and sharing of manufacturing resources. As most elevator enterprises are small and medium-sized, there are common problems in the process of elevator design and manufacturing, such as low manufacturing level, long design verification time, and poor sharing ability of manufacturing resources. The cloud manufacturing service platform for elevator industry alliance is the application and landing of CMfgIA in the elevator industry alliance, and can provide manufacturing services such as design service, processing service, assembly service, and testing service for members in the elevator industry alliance.

Elevator design is the most important part of the entire product development process because it is the foundation of the later parts processing, assembly and type testing. Restricted by the national design standard (e.g., GB7588), elevator design business process of different enterprises have commonality. This section takes the elevator design process as an example to elaborate the manufacturing service development process and service mode of the platform.

To guide the development of manufacturing services for the service providers, the domain experts (including elevator designers) conclude the common design requirements and personalized design requirements in the process of elevator design, then construct the feature model (shown in Fig. 5a) and extract the atomic features. Figure 8 shows the two-phase development process of manufacturing services based on feature models.

In the first phase (Fig. 8a), when the alliance member publish a new manufacturing service, the corresponding service domain need to be selected. A service domain

Fig. 10 Management and execution of the multi-granularity design system



represents an atomic feature. For example, if the alliance member want to publish power calculation service, the item of power calculation needs to be selected. After that, the mapping relationship between atom-level manufacturing service and atomic feature is established. Then, other basic information (e.g., service URL, input parameters, output parameters) of manufacturing service needs to be added step by step. The information of atom-level manufacturing service is stored in an XML file. As more and more manufacturing services registered in the platform, the atomic manufacturing services library is built.

In the second phase (Fig. 8b), enterprises can order the elevator design system by selecting atomic features in the feature model (expressed in a tree-like structure). Then, a customized feature model which contains the service composition process information is obtained. Based on the customized feature model, the platform gives an suitable instance through new service composition or existing case reuse automatically. Each service composition instance stands for a coarse-grained manufacturing service. And these information is stored in a Json file. Gradually, the coarse-grained manufacturing services obtained are stored in the platform and multi-granularity manufacturing service libraries are established.

The developed manufacturing services can be modified and deleted according to the practical requirements in the industry alliance. What's more, some manufacturing services may become invalid sometimes. In order to ensure the validity of manufacturing service during the service execution, the platform provides a tool for testing these services. Figure 9 shows the testing process of manufacturing service.

As shown in Fig. 9, the tractor torque verification service is used as an example to illustrate the testing process of manufacturing service. It is a coarse-grained manufacturing service which consists of seven atomic manufacturing services. Firstly, the tractor torque verification service is dragged to the testing area and transformed into a visual structure which presents the service composition process information. Each circle represents an atomic manufacturing service and the arrow represents the composition relationship between two services. Secondly, the atomic manufacturing service needs to be executed in sequence. The circle will turn to be blue when the atomic manufacturing service has been executed successfully. And the invoking results is shown in the invoking log. The manufacturing service is valid if all of the circles become blue in the end.

For enterprise users, they can conveniently use and manage the ordered design service systems in the platform. Figure 10 shows the management and execution of the multi-granularity design system for Lincoln elevator company (a member in the elevator industry alliance).

Due to the diversity of enterprise design requirements, multiple design service systems with different granularities have been ordered. For example, the elevator design service system (Fig. 10b) and escalator design service system (Fig. 10c) are product-level manufacturing service, balance system design service system (Fig. 10d) is system-level manufacturing service and tractor torque design service system (Fig. 10e) is unit-level manufacturing service. Through these design service system, elevator designers can efficiently complete the elevator design or part design of the elevator. When designing, the designer need to choose and enter into a required design service system. A design service system contains several web pages and each page represents a design business activity in the elevator design process. Each design business activity should be finished by invoking and executing corresponding manufacturing service. Figure 10f, g are the design pages of the elevator design service system and tractor torque design service system respectively. As shown in the figures, the tractor design service system is a part of the elevator design service system.

Actually, the cloud manufacturing service platform is on trial in the elevator industry alliance. It shows that the cloud manufacturing platform for the elevator industry alliance helps to solve the practical manufacturing requirements of the alliance members. It improves manufacturing level, reduces manufacturing costs, shortens the manufacturing cycle, and enhances their competitiveness. For example, in the elevator design period, the design cycle could be reduced to 70% averagely.

6 Conclusions

In order to realize the effective sharing of manufacturing resource in the industry alliance, a cloud manufacturing application mode for industry alliance called CMfgIA is proposed in this paper. The CMfgIA can provide common manufacturing services and personalized manufacturing services for alliance members on demand, and enhance the overall manufacturing level of industry. For the purpose of guiding the servitization of manufacturing resource, the domain-driven development approach for multi-granularity manufacturing service is adopted. The approach realizes the granular modeling and management of manufacturing services. Through the reuse of feature models (i.e., domain requirements models), service composition process and service composition instances, the problems of long period matching and messy manufacturing services could be solved. Finally, the elevator industry alliance is taken as an application example and the feasibility and effectiveness of CMfgIA is proved. More importantly, the CMfgIA provides a practical solution for the landing of cloud manufacturing.

As future work, we would like to promote the platform and obtain more data from the users to optimize the feature model library. Another direction is to expand the approach in other domains such as the manufacturing of crane, pressure vessel, and other special equipment.

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