Investigation on Digital Twin Enterprises with an Architecture-Driven Modeling Approach in Cloud Manufacturing

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Abstract: The cloud manufacturing required by an increasingly dynamic competitive industrial environment results in the formation of "digital twin enterprises". In order to investigate the digital twin enterprise with an architecture-driven modeling approach, this paper first introduces the essential elements of the digital twin enterprise architecture. These elements are converged by the multi-agent technology to form digital resources that can be dynamically connected to the cloud manufacturing platform. Then, by combining the digital twin technology, the general activities of enterprises are further refined to form the main operation flow of the architecture. Finally, as the digital twin technology is the core supporting technology for cloud manufacturing, this paper conducts a detailed analysis of the process of digital twin enterprises participating in cloud manufacturing. Through the application of digital twin technology, enterprises can reasonably control their production resources, and the internal production data flow can be further utilized to optimize the production process. Meanwhile, the manufacturing resources of enterprises can be accessed to the networked manufacturing platform in real time, and personalized orders can be obtained and further exploited according to the enterprise's real status. The digitalization degree of enterprises has been greatly improved by constructing the multi-agent operation framework and optimizing the process of enterprises participating in networked production activities.

Key words: cloud manufacturing; digital twin (DT); multi-agent; enterprise activity

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0 Introduction

Today, consumers' calls for personalization is evert demanding. It requires frequent product improvements, immediate delivery, guaranteed reliability, and ever-decreasing prices. The relative evolutions of the incandescent light bulb and the light-emitting diode (LED) are examples that reflect the relationship between consumers and products. While the incandescent light bulbs have been the dominant mode of flare area for almost 80 years, LEDs have replaced them as mainstream in just ten years, with many significant enhancements and extensions being announced as the technology evolving. Therefore, for manufacturers, limitations on capital investment, requirements for changed machines and resource configurations, and the need to minimize stock levels bring tremendous pressure and challenges to the manufacturing pattern[1].

With the accelerated pace of scientific and technological progress in the 1990s, researchers increasingly sought to create a circumstance that is adaptive and responsive for customized production. After a short while, the concept of cloud manufacturing was proposed by Li et al.[2] and attracted extensive concern and attention from governments, industrial com-

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munities, and enterprises. Among them, enterprises are most concerned about participating in cloud manufacturing and applying cloud manufacturing technology for more profits. Driven by the related information technology, cloud manufacturing combines the actual demands in the industrial community, adopts advanced manufacturing technologies, and becomes the typical representative of the next phase of industrial informatization development[3].

Cloud manufacturing is a "software facility" that combines advanced information technology, manufacturing technology, and emerging networking technologies. This software facility integrates existing information technologies, such as digital twins (DTs), cloud computing, networking, and multi-agent technology, to realize uniform, centralized and intelligent management of manufacturing resources, providing safe, reliable, and cost-effective intelligent service according to the exact needs[4]. Although cloud manufacturing has many advantages, the current enterprise information level is not enough to support the actual operation of cloud manufacturing[5].

Cloud manufacturing enterprises refer to the production enterprises involved in the cloud manufacturing process[6]. Cloud manufacturing is a new mode of network manufacturing, which uses the network and cloud manufacturing service platforms to organize online manufacturing resources according to users' needs, and provides customers with all kinds of on-demand manufacturing services. However, the digitalization degree of enterprises involved in cloud manufacturing varies. Cloud manufacturing enterprises with a low degree of digitalization cannot share their production status with the cloud manufacturing platform in real time. They rely on repeated manual confirmation of enterprise status, leading to substantial lag on the opposite side of receiving orders. Thanks to the emergence of the digital twin technology, enterprises can carry out digital transformation to meet the needs of cloud manufacturing, sort the complicated and disordered data flow of enterprises, integrate their own resources into manufacturing service better, interact with the cloud manufacturing platform in real time, and obtain orders more suitable for enterprise production. In summary, digital twin enterprises can better participate in networked manufacturing.

1 Digital Twin Enterprise Architecture

DT enterprises are combinations of resource, product, and order DTs that work together to virtualize the physical enterprise layer, optimize control, assure resource health, and face disturbances in a mode of agility[7]. A DT enterprise is also a collection of enterprise activities organized into business processes that collaborate to produce the desired results. Aggregating resources, products, and orders can be valuable for enterprise activities to realize real organizational value, which is the essential component of an enterprise. Only by combining these three elements can enterprise activities become useful and increase the real organizational value.

The aggregation of enterprise elements is the basis of the DT enterprise architecture. With the help of these aggregation elements, this paper combines DTs in industrial and the regular operation of the enterprise in cloud manufacturing to form the generic enterprise architecture[8]. This structure is a model that integrates diverse views and is used to completely describe the whole business activities of the DT enterprise. Under the DT enterprise architecture, the traditional enterprise has failed to meet the demand. Based on this, new requirements are needed it. The main contents include:

(1) All types of resources in an enterprise can access the cloud platform securely and efficiently.

(2) DT technology should be applied to map enterprise resources, orders, and products and in-depth simulation and prediction shoule be carried out.

(3) The above resources are dynamically linked through enterprise activities.

(4) The definitions and functional descriptions of the cloud manufacturing service platform should be designed and realized.

In the DT enterprise, the aggregation of resources, orders, and products means connecting the various manufacturing resources into the cloud manufacturing service platform, and encapsulating them to form services that can be managed and controlled by the cloud manufacturing service platform. Thus the proper allocation scheduling of resources can ultimately be achieved[9]. As shown in Fig.1, the top-level activity view of the DT enterprise includes the following modules:

(1) DT in industrial. This module is the most important in the DT enterprise architecture. It will collect necessary information from all aspects of enterprise activities, conduct real-time simulation and prediction through the usual activity rules of the enterprise, and provide in-depth guidance for the whole enterprise to participate in the cloud manufacturing process.

(2) Manage resources. This module concerns the management of resources, including capital, personnel, information, and facilities. Besides, this module also converts the prediction and simulation in the DT module into an executable plan, affecting each level's subsequent actions.

(3) Market product. This module provides the DT enterprise with its dynamic external links to customers and the industrial environment. It is responsible for identifying and decomposing customer requirements that can be translated into available information for the manufacturing department. Order agents and product agents are the responsibility of this module.

(4) Conduct manufacturing operations. This module ensures the efficient production of the enterprise through the precise execution of other modules. At the same time, it combines DT modules to ensure sufficient resources to meet production requirements and control the use of these resources.

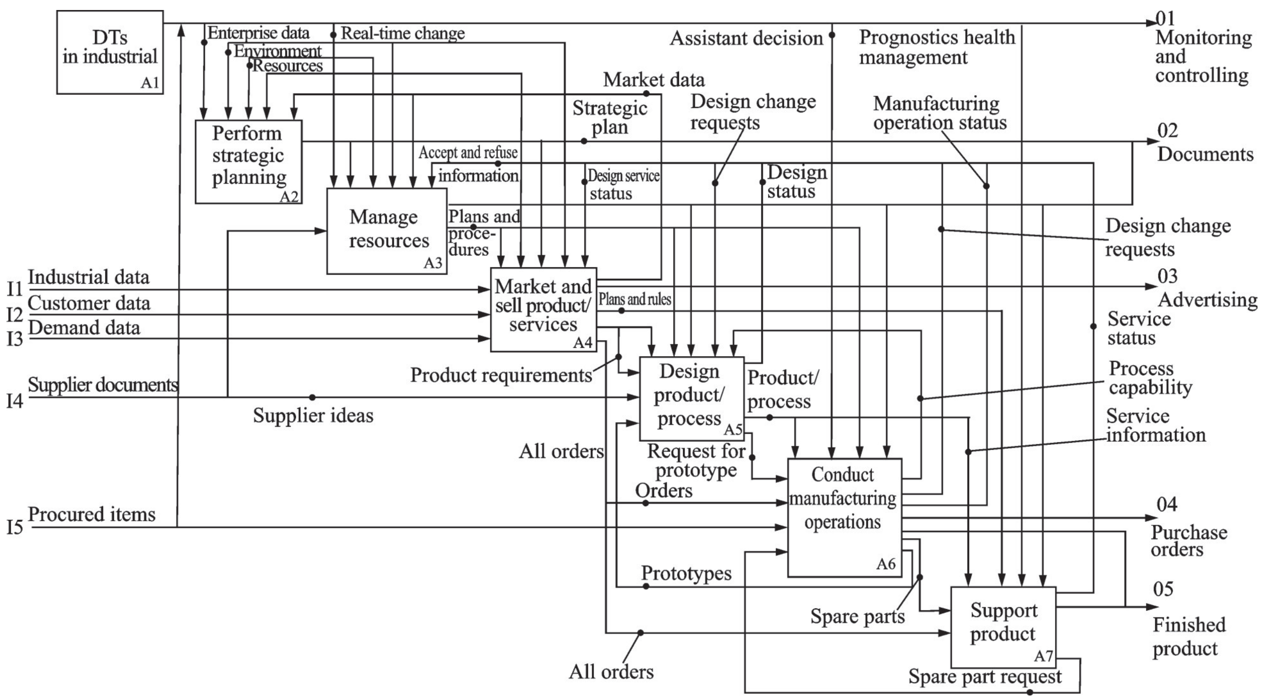

Fig.1 Top-level activity view of the DT enterprise

2 Basic Elements in Enterprise Architecture

The premise for enterprises to participate in cloud manufacturing is digital management and the application of their related elements. At the same time, the importance of these elements in the general activities of the enterprise cannot be ignored. This paper combines multi-agent technology to aggregate the essential elements of a DT enterprise. There are three types of agents in the DT enterprise, namely resource agents, product agents, and order agents[10].

A resource agent can be divided into a physical part and a virtual part, that is, a production resource of the physical part, and an information processing part that controls the resource of the virtual part. It is the subject of receiving order information during the production process and the carrier of product information dissemination. It can allocate production resources, and different types of resource agents can interact with each other in real time to promote production[11].

A product agent has all the knowledge and logic to complete the product production. It is used to ensure the correct production of products and responsible for monitoring product quality[12]. The product agent mainly maintains all information about the product life cycle, user requirements, process plan, bill of materials, and quality assurance procedures and dynamically updates the information according to the real-time production situation. The product agent performs as a server to other agents in the DT enterprise[13].

An order agent represents a task received from the cloud manufacturing platform. Then, the order agent can allocate tasks in time and correctly through dynamic interaction with the resource agents. It mainly manages the physical products, virtual twins, and all relevant information related to production tasks. In addition, the order agent can be regarded as a workpiece with specific control behavior, and will also record all activities of the "workpiece" in the production life cycle[14].

In the DT enterprise, the resource, product, and order DTs are combined to virtualize the physical shop floor in order to optimize control, which can assure resource health and face disturbances in an agile mode[15]. Agents in DT enterprises are mainly used to drive virtual twins. By establishing models and rules that map physical entities, agents are endowed with the ability of self-learning to carry out efficient self-organizing work in DT enterprises.

DTs bring additional information about resource behaviors, cost of use, history of use, covariance of operating parameters, real time performance evaluation, etc., allowing predictive reconfiguration of job scheduling and resource allocation[16]. Therefore, aggregated agents are defined as a set of related agents that are clustered together to form a high-level agent with their own identities. Thus, an aggregation hierarchy is formed, which is open-ended at the top and bottom. Depending on the study scope of the observer, agents are split up into their sub-agents or treated as a whole.

As shown in Fig.2, every line represents a relation. A line with a diamond represents the aggregation relation. The DT enterprise has product agents, resource agents, and order agents. The specialization relation is represented by a line with an arrow. The association relation is represented by a standard line. As shown in Fig. 2, both ends of the line usually have numbers associated with them. This is called the cardinality (i.e., 0..*, 1..*, and 1), and it represents the number of this type of agents that are involved in this relation. The DT enterprise contains at least one resource agent, and it may contain zero or more order agents. The DT enterprise also contains zero or more product agents. When containing zero order agent, the MAS is idling. Fig. 2 also shows that multiple (0..*) order agents can refer to the same kind of product. However, every order agent refers to exactly one product agent. After completing the architecture design according to the functional attributes of the edge gateway in cloud manufacturing, it is necessary to implement the enabling technology of each layer. One of the most important techniques is the combination of the microservices and intelligent edge gateways.

In short, the basic unit of a DT enterprise is a multi-agent system capable of mapping physical entities. By using DT technology, the aggregation of multi-agent system (MAS) information is at a high level so that the activities and operation of the DT enterprise are more efficient. The industrial data in the DT enterprise is organized flexibly, which enables the DT enterprise to participate better in networked manufacturing[17].

As shown in Fig.3, the essence of a DT enterprise is a multi-level hybrid enterprise architecture model, including individual units, workstations, shopfloors, factories, and other multi-level control elements. Meanwhile, DT technology maps, man-

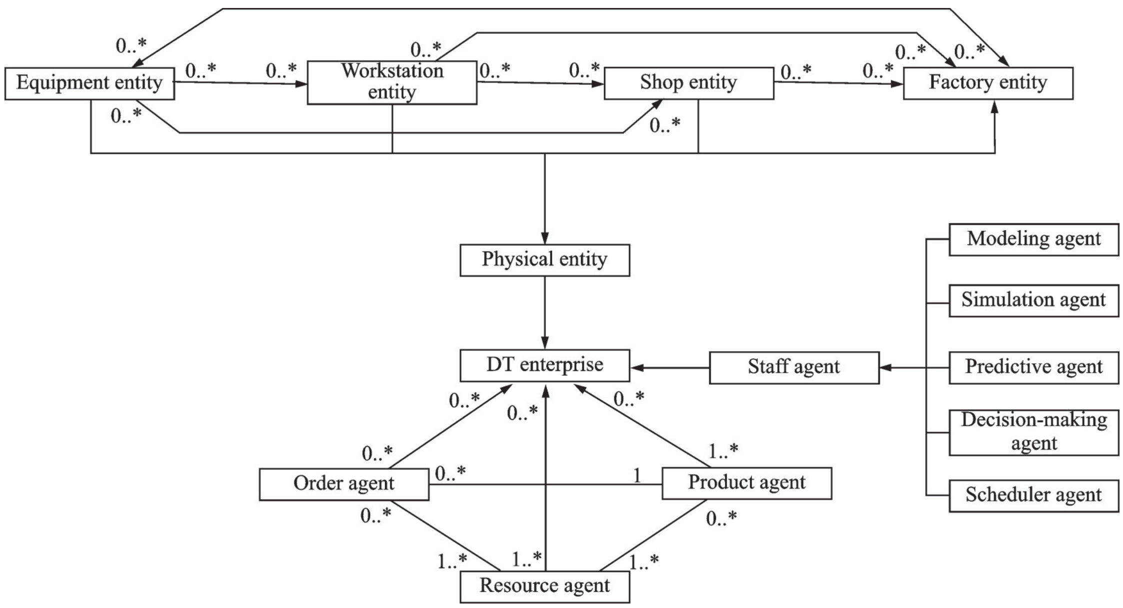

Fig.2 Aggregation of enterprise elements

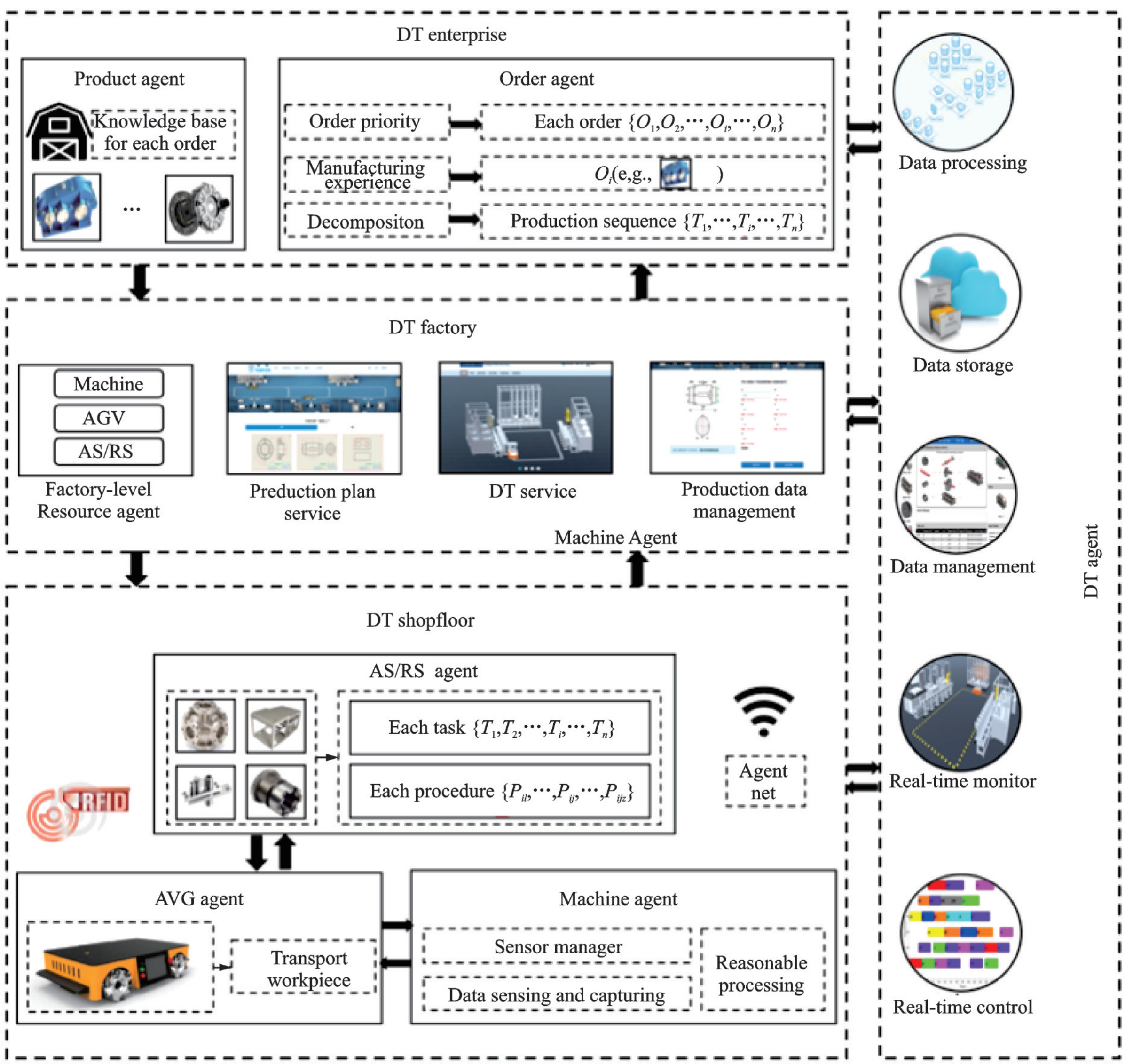

Fig.3 Working mechanism of DT enterprises

ages, and controls the data of key elements at each enterprise level. Multi-agent technology is the core component of a DT enterprise. In the top-level management and control of a DT enterprise, the manufacturers grasp the internal and external conditions of the enterprise through the order agent and the product agent. The product agent processes the product information that the factory needs to produce, grasps the enterprise's core production experience, and develops the knowledge base to cope with various orders. The order agent is mainly responsible for breaking the received order into a production queue that factories can complete. At the level of a DT factory, resource agents mainly manage and control the shopfloor resources (e.g., machine tools, automated guided vehicle (AGV), automated storage and retrieval system (AS/RS)) in real time, and provide production planning services, shopfloor monitoring services and production data management services. These functions can easily manage and adjust the working operation of the shopfloor. At the level of the DT shopfloor, realizing the self-organizing production of the shopfloor production unit is a priority. Here, the interaction among AS/RS, AGV, and machine tools in the shopfloor is taken as an example. When the AS/RS agent receives the tasks from the factory level, the tasks are sorted according to priority and further decomposed into the operation procedures that the machine tools can process. Meanwhile, the AGVs will be arranged to transport the workpiece according to the sequence of the processes, and the machine tools will process the in-process according to their respective operating procedures. By the way, all the production resources are embedded with agents, and production tasks are allocated through the interaction among agents. Based on this, the self-organizing production of the products is realized through iteration. DT agents continuously map, store, and manage the data of these agents, which monitor and control the production process in real time. The real time calculation and prediction of the DTs agent can accurately provide feedback for other agents, help to manage their own functions in an orderly way, and ensure smooth information exchanges among heterogeneous agents. The application of DTs in enterprises' production control can help enterprises control their production process more accurately. At the same time, the production data has been more comprehensively utilized, and the visual production scene can accurately reflect the problems existing in the production of enterprises.

3 Case Study

Cloud manufacturing aims to offer users (consumers, manufacturers, and designers) the total life cycle of available, reliable, and cost-effective manufacturing services to satisfy their needs at any time, anywhere. However, the premise of realizing cloud manufacturing is to build a large-scale link pool for enterprises, while the DT and multi-agent technology are the cores to support this application. The cloud manufacturing processes based on DT enterprises are shown in Fig.4.

3.1 Cloud manufacturing realization process

DT enterprises realize the integration of enterprise resources so that the enterprise's manufacturing capabilities can be dynamically presented on the cloud manufacturing service platform through a series of numerical values. Furthermore, DT enterprises can participate in the cloud manufacturing process with their enterprise activities and needs. As the number of DT enterprises grows to a specific size, they need to have the infrastructure to connect resources to the cloud in an orderly and efficient way (usually through the Industrial Internet of Things). Enterprises' own outsourcing needs can also be realized through platform services.

In the cloud manufacturing service platform, management, simulation, logistics, security, and other functions need to be encapsulated as services so that DT enterprises can participate in the whole production process through service-oriented functions. Cloud manufacturing service platform connects actual DT enterprises' manufacturing resourc-

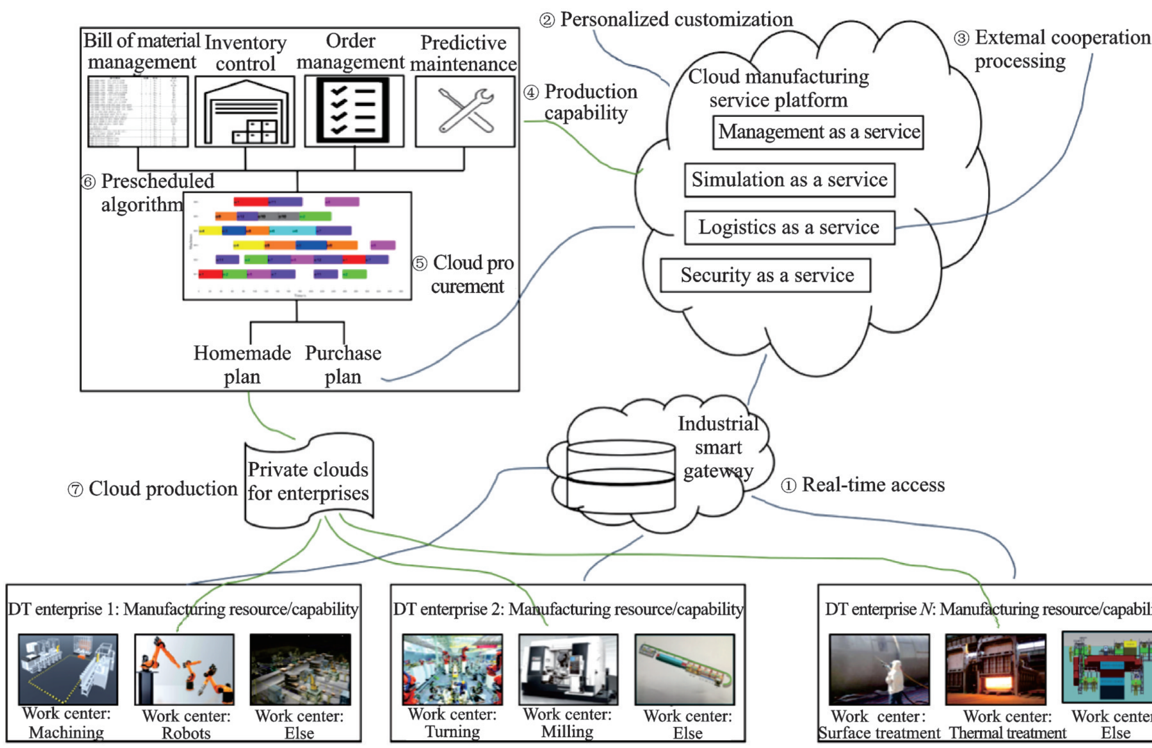

Fig.4 Cloud manufacturing mode based on DT enterprises

es to conduct unified management and control through the application of multi-agent technology. Here, a highly customized product is taken as an example. The production process involves multi-regional cooperation. When the platform receives a personalized customization demand from users, the production activities of DT enterprises often start formally. When an order is received by the cloud, the order agent in the cloud is responsible for decomposing users' personalized customization requirements (order) into manufacturing tasks that can be produced according to DT enterprises' manufacturing capacity, quotation, and competition rules. The product agent learns the corresponding production knowledge according to each task and sends the manufacturing characteristics to the resource agent. Since the production information of the DT enterprise is highly aggregated, the main production capacity will be encapsulated into services and aggregated in the resource pool of the cloud. Resource agents in the cloud match the service based on the manufacturing characteristics of each task. This process will generate a series of complex production plans in the cloud. When a user finalizes a specific contract, the DT installs the contract and starts cloud manufacturing. Finally, the DT enterprises involved in networked manufacturing coordinate different parts of the order in a well-aligned manner.

3.2 Functions and significance

In the whole process of cloud manufacturing, three crucial functions need to be realized: Self-organizing perception and management of enterprise resources based on DT technology; efficient, safe, and dynamic access of enterprise resources to cloud manufacturing service platform; and self-operation and maintenance of cloud manufacturing service platform.

In DT enterprises, the combination of multi-agent technology can efficiently integrate the resources, orders, and products within the enterprise and facilitate the digital and automatic management of enterprises. The structures in multi-agent technology can also be inherited by DT enterprises, both bottom-up and hybrid. This is the key for enterprises to form the main body of cloud manufacturing. As a prominent part of the cloud manufacturing process, the rules of enterprises participating in cloud manufacturing are fundamental. In the DT enterprise architecture proposed in this paper, the dynamic activities of the enterprise are more clearly described.

The cloud manufacturing service platform puts more emphasis on the operation and management of platform services and needs enough computing power to integrate the dynamic resources of enterprises and the personalized customization needs. The breakdown of any link will destroy the cloud manufacturing service platform, thus affecting the progress of cloud manufacturing. Therefore, the security operation of the cloud manufacturing service platform plays a vital role in the whole cloud manufacturing process.

4 Conclusions

This paper introduces a DT enterprise architecture, which satisfies the needs of modeling a DT enterprise. The shortcomings of current manufacturing techniques are also discussed, especially concerning the DT enterprises. Autonomous agents and ontologies are applied to cover hierarchical and heterarchical control approaches in helping engineer and improve processes within the DT enterprise. We then describe some applications that are applied to cloud manufacturing. These applications can model and map the enterprise from viewpoints that combine the general processes of cloud manufacturing with the DT enterprise.

To date, the methodological tools and techniques for engineering DT enterprise have been applied to limited processes. There are a few potential reasons for this: (1)A true cloud manufacturing platform that is suitable for DT enterprise does not exist. (2)At present, the industry has formed some dynamic network organizations to a certain extent, but the DT enterprises in line with the actual situation as the paper mentioned have not yet appeared. (3)The field of cloud manufacturing is attracting more researchers to develop and understand DT enterprises.

In summary, the developed DT enterprise is proposed to make cloud manufacturing a practical application to meet the present global economic circumstances. In order to help the enterprise manage the production data more flexibly and probe the DT enterprise, a multi-agent-based DT enterprise framework is proposed, which can dynamically access the manufacturing resource to the cloud in real time and receive the personalized customization orders according to the actual needs and working state of the enterprise. Based on this, the essential elements of the DT enterprise and the working mechanism of the multi-agent framework in DT enterprises are introduced further to refine the main operation flow of the enterprise. It is noted that the proposed method with the asynchronous structure has superior self-organization performance and higher efficiency compared with the origin. At the same time, the proposed approach is blended with intelligence, which will help DT enterprises produce high-quality products and manage resources to solve problems encountered during the ordinary course of the operation. As a new emerging concept, cloud manufacturing still has significant room for improvement. Future work will establish an actual DT enterprise model to help enterprises participate in networked collaborative manufacturing.

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Author contributions Mr. **NIE Qingwei** designed the methodology, complied the models and the software, and wrote the manuscript. Dr. **ZHU Haihua** contributed to the result interpretation and the manuscript revision. Prof. **TANG Dunbing** raised the idea. Mr. **WANG Liping** completed the interview and assessment. Mr. **SONG Jiaye** designed the case study. Mr. **LIU Changchun** contributed to conclusions and background. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

在云制造背景下用架构驱动的建模方法探讨数字孪生企业

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摘要：日益动态竞争的制造、商业和工业环境所要求的云制造，导致了“数字孪生企业”的形成。为了用体系结构驱动的建模方法探索数字双胞胎企业，本文首先介绍了数字孪生企业体系结构的基本要素，利用多智能体技术将这些要素聚合形成资源，并动态连接到云制造平台。然后结合数字双胞胎技术，进一步细化企业的一般活动，形成体系结构的主要操作流程。最后，本文对数字孪生企业参与云制造的过程进行了详细的分析。通过应用数字孪生技术，企业能够对自身的生产资源进行合理的管控，企业内部的生产数据流得以被进一步利用，使得生产过程得到了优化。同时，企业的制造资源能够实时接入网络化制造平台，更好地获取适合生产的个性化订单。本文通过构建多智能体运行框架，优化企业参与网络化生产活动的流程，使得企业本身的数字化程度得到了极大的提升。

关键词：云制造；数字孪生；多智能体；企业活动