International Journal of Multidisciplinary Engineering in Current Research
ISSN: 2456-4265, Volume 6, Issue 5, May 2021, http://ijmec.com/

WEAKNESS IN OPTIMIZATION OF CLOUD MANUFACTURING PROCESS UNDER VARIOUS RESOURCE EXCHANGE STRATEGIES

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Abstract: Cloud manufacturing is characterized by large uncertainties and disturbances due to its networked, distributed, and loosely coupled features. To target the problem of frequent cloud resource node failure, this paper proposes (1) three resource substitution strategies based on node redundancy and (2) a new robustness analysis method for cloud manufacturing systems based on a combination of the complex network and multi-agent simulation. First, a multi-agent simulation model is constructed, and simulation evaluation indexes are designed to study the robustness of the dynamic cloud manufacturing process (CMP). Second, a complex network model of cloud manufacturing resources is established to analyze the static topological robustness of the cloud manufacturing network. Four types of node failure modes are defined, based on the initial and recomputed topologies. Further, three resource substitution strategies are proposed (i.e., internal replacement, external replacement, and internal–external integration replacement) to enable the normal operation of the system after resource node failure. Third, a case study is conducted for a cloud manufacturing project of a new energy vehicle. The results show that (1) the proposed robustness of service index is effective at describing the variations in CMP robustness, (2) the two node failure modes based on the recalculated topology are more destructive to the robustness of the CMP than the two based on the initial topology, and (3) under all four failure modes, all three resource substitution strategies can improve the robustness of the dynamic CMP to some extent, with the internal–external integration replacement strategy being most effective, followed by the external replacement strategy, and then the internal replacement strategy.

Keywords: cloud manufacturing; robust optimization; resource substitution; complex network; multi-agent simulation

1. Introduction

In the era of Industry 4.0, with the rapid development of Internet technology, information technology, and manufacturing technology, the traditional large-scale manufacturing mode is gradually being replaced by customized service modes. A series of advanced networked manufacturing modes, such as application service providers, manufacturing grids, agile manufacturing, and global manufacturing have been proposed successively. The concept of "cloud manufacturing"—a new service-oriented networked manufacturing mode that gathers manufacturing resources and capabilities together on the cloud platform, escaping the limitations of space and distance; through service integration, the sharing of manufacturing resources and capabilities is fully realized. Since its inception, cloud manufacturing has attracted widespread attention because of its advanced ideas and technical concepts.

The cloud manufacturing mode extends the manufacturing environment to multiple user subjects, service subjects, and geographical spaces. As such, it faces a high level of uncertainty and disturbance. The cloud manufacturing system (CMS) can reduce the impact of some disturbances (e.g., demand change, order fluctuation, and emergency order insertion) through its own flexible configuration and self-adjustment strategies, but relatively serious disturbances can cause a variety of damage, such as insufficient supervision of the cloud platform, random the withdrawal of cloud service providers from the platform, the failure of cloud resource nodes, and the interruption of cloud paths, among others. Therefore, it is of great practical significance for the implementation and deployment of cloud manufacturing projects to accurately identify the impact of uncertain environments on cloud manufacturing , explore the robustness level of the cloud manufacturing process (CMP) under different interference modes, and formulate corresponding robustness recovery strategies to improve the stability and anti-interference of the system .

2. Related Works

2.1. Robustness Analysis Study of Manufacturing Systems

Many scholars have conducted research on the robustness of advanced manufacturing systems and networks. Gao et al. applied complex network theory to the manufacturing industry, proposing the construction method of the complex network failure model. The vulnerability of the manufacturing network may lead to new risks; they analyzed the topology structure and vulnerability of the cloud manufacturing network (CMN) and put forward management suggestions. The impacts of interruption events on the entire industrial system and proposed a cooperative repair approach based on a distributed industrial system to limit these impacts. established a collaborative manufacturing services network model using the complex network method, defined six fault types, and proposed corresponding fault detection methods. Further, the cascaded propagation characteristics of different faults were revealed, and corresponding control strategies were proposed. The analyzed the changing individualized requirements, risks, and possible solutions in cyber- physical systems. The proposed a decision support method for the terminal management process of a cyber-physical production system, modeling and simulating respective scenarios of interruption events and response strategies. E stablished the process relationship network of the flexible job shop by analyzing the relationships among basic production factors, such as machines and workpieces in the shop. They proposed adaptive preventive maintenance and buffer time insertion strategies. Zhang proposed the definition of the manufacturing product assurance network; they established an evolutionary model of the manufacturing product assurance weighted network on this basis, and then analyzed the robustness characteristics of the network.

Such research demonstrates that cloud manufacturing and other advanced networked manufacturing modes have large uncertainties and risks due to their networked, dis- tributed, and loosely coupled characteristics. Robustness analysis of these modes has become a popular issue in academic circles, with many scholars exploring this from a variety of perspectives.

2.2. Robustness Enhancement Strategies and Recovery Measures

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The specific robustness enhancement and defense strategies vary from network to network, but from the perspective of a network structure, establishing redundant nodes or links is one of the most common methods to improve network robustness. As early as 2005, the proposed that people are usually faced with the problem of improving the robustness of an existing network that cannot be substantially modified or redesigned: only minor modifications are allowed, such as adding new nodes, reconnecting partial edges, or adding new edges. As stated, that the robustness of the whole network can be improved by increasing the number of reliable nodes in the network or improving the reliability of a small number of nodes in the network. The argued that it is impossible to enhance the reliability of every node in the network, so it is instead necessary to specify the priority of nodes and links and focus on their protection.

Regarding the study of reliable nodes, the proposed a heuristic scheduling rule based on controlling critical nodes for the scheduling optimization of the job shop in a disturbed environment, and used both the improved node shrinkage method and the triangular fuzzy number method to comprehensively evaluate the importance of nodes in the network, proposing corresponding improvement measures in terms of critical node protection. Regarding the study of adding links (i.e., connected edges), proposed two new strategies: low inter degree–degree difference addition and random inter degree–degree difference addition. They verified the effectiveness of these proposed strategies through a comparison with four existing link-addition strategies (i.e., random addition, low degree addition, low betweenness addition, and algebraic connectivity-based addition). proposed a preferred connectivity strategy based on the structure of inter- dependent networks. They applied this strategy to three existing link-addition strategies (i.e., random addition, low degree addition, and low inter degree–degree difference addi- tion), finding that each improved strategy was significantly better than the previous one in terms of robustness improvement. The effects of link-addition strategies on the improvement of the robustness of different networks have been further investigated .

Measures such as adding redundant nodes and connected edges can effectively im- prove network robustness. As such, these measures are receiving increasing attention from scholars, and they also provided ideas for the design of the cloud manufacturing-based robustness improvement strategy in this paper. Targeting the problem of frequent cloud resource node failure, this paper attempts to establish redundant nodes so that appropriate alternative resources can be used to avoid the complete breakdown of the manufacturing process or system when the original manufacturing resource nodes fail. Based on this and the background characteristics of cloud manufacturing, this paper presents three kinds of robustness improvement strategies: internal resource replacement, external resource replacement, and internal–external integration replacement.

2.3. Multi-Agent Simulation Study of Cloud Manufacturing System

The existing research on the robustness of advanced manufacturing systems mostly uses the complex network analysis method, which is well suited to reflect the structural characteristics of the system. As a type of networked manufacturing mode, the structural characteristics of cloud manufacturing is a key topic in robustness research; however, the dynamic operation process, logical judgment, and dynamic temporal relationship among entities are also aspects of cloud manufacturing that should be focused on.

The CMS contains a variety of entities, and various forms of behavior interaction and information transfer exist between the same entities and different entities, showing the characteristics of the complex system. Analyzing the complexity through simple, intelligent, and autonomous entities, such as agents in multi-agent systems, is considered an appropriate approach to address this challenge in industrial scenarios. Further, the multi-agent simulation modeling of the CMS is presently a popular research topic. For example, Zhao et al. designed and implemented an agent-based cloud manufacturing simulation platform, where the simple reflective agent was used to encapsulate the resources and the complex agent was used to encapsulate the services. This gave the cloud platform a five-layer architecture (i.e., the data layer, low tool layer, management layer, upper tool layer, and application layer). proposed a cloud simulation platform to provide computing resources and services for the hybrid simulation of virtual manufacturing systems, and developed a cloud-based factory simulation experiment system. analyzed typical smart manufacturing simulation techniques from three aspects: manufacturing unit simulation, manufacturing integration simulation, and manufacturing intelligence simulation. In addition, some scholars have conducted multi-agent simulation modeling research on cloud manufacturing from multiple perspectives, such as cloud service entity encapsulation, selection and scheduling , and trust and security issues , among others. Multi- agent simulation has become an important tool for cloud manufacturing research, yet current multi-agent simulation research on the robustness of cloud manufacturing appears relatively rare.

This paper proposes a robustness analysis method that combines the complex network and multi-agent simulation to investigate the optimization and enhancement of CMS robustness under multiple resource substitution strategies. The complex network perspective can reflect the structural robustness of CMSs, while multi-agent simulation can consider the process robustness of CMSs from multiple dimensions, such as time, cost, quality, and reliability. The combination of these two perspectives extends the robustness analysis object of the CMS from the CMN to the CMP, thereby realizing the dual-dimensional analysis of the static structure and dynamic process of CMS robustness.

The rest of this paper is arranged as follows. Section 3 constructs a multi-agent simulation model of the CMP and proposes process robustness indexes from the simulation perspective. Section 4 establishes a complex network model of cloud manufacturing resources and selects structural robustness metrics from the network perspective. Section 5 defines four types of resource node failure modes and three types of resource replacement strategies to deal with resource failure. Section 6 conducts a case study, combining multi-agent simulation software Anylogic and Python 3.0 tools to study the changes in the robustness of cloud manufacturing under different failure modes. Section 7 provides the research conclusions and future prospects.

3. Model of the Cloud Manufacturing Process and Robustness Evaluation Indicator Based on Multi-Agent Simulation

3.1. Construction of Multi-Agent Simulation Model

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The cloud platform, cloud task, cloud resource, cloud message, cloud order, and other types of subjects are all contained in the CMS, along with two different types of user roles: cloud service providers and cloud demanders [41]. The CMP [2] basically entails the following, as indicated in Figure 1:current multi-agent simulation research on the robustness of cloud manufacturing appears relatively rare.

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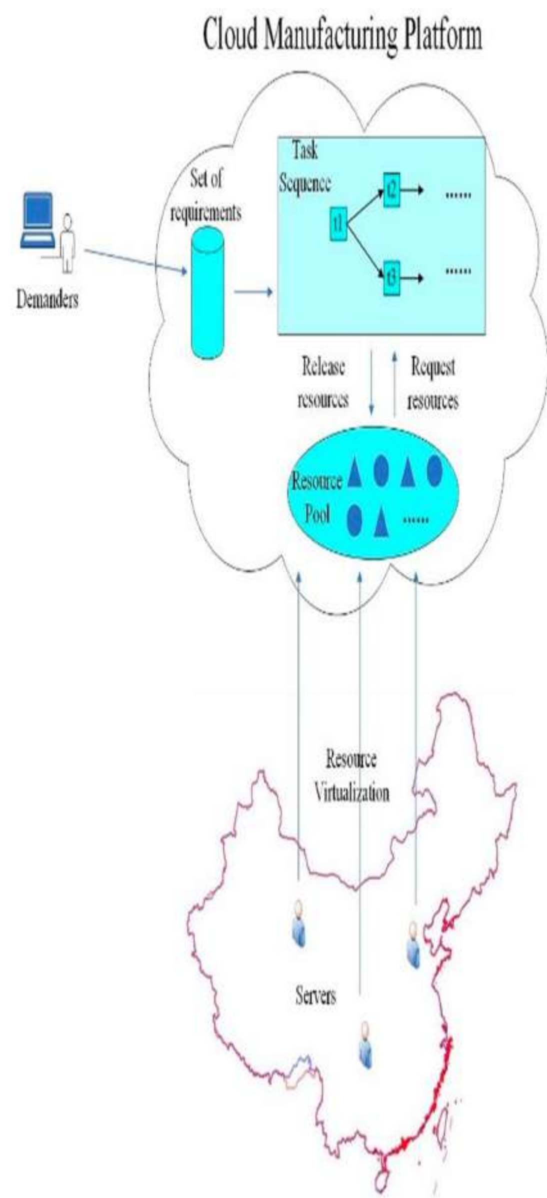

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Figure 1. Schematic diagram of CMP.

Through information transformation, resource sensing, resource access, unified modeling of cloud services, and other technologies, cloud service providers integrate different kinds of manufacturing equipment and manufacturing capability resources into the cloud platform and deposit them into the cloud resource pool. This allows globally distributed resources to be managed and shared centrally, thereby circum- venting the spatial and geographical limitations.

Utilizing terminal devices, cloud demanders submit their requests for services (i.e., orders) to the cloud platform. The cloud demand set uniformly stores orders awaiting processing from various cloud demanders.

In accordance with the service route of the to-be-processed order, the cloud platform integrates and adapts various cloud tasks to create structured and reliable cloud task sequences.

In order to perform cloud manufacturing services, the platform imports each order into the appropriate cloud task sequence when the cloud demand set is not vacant. Based on the task type, the appropriate resources are requested from the resource pool while processing Modeling of Cloud Resource Agent .Through information transformation, resource access, cloud service unified modeling, and other technology, service providers' manufacturing equipment and manufacturing capacity resources are integrated into the cloud resource pool to create virtual resources known as cloud resources. The primary function of the cloud resource agent is to collaborate with cloud tasks to finish the processing of cloud orders:

$$RA_0=\langle ID, produceLevel, busy, broken, owner, price\rangle \quad (2)$$

where ***ID*** represents the resource's special identification number; ***produceLevel*** is an in- teger ranging from 1 to 10 that specifies the resource's productivity level; ***busy*** indicates whether the resource is in a busy condition; ***broken*** shows whether the resource is defective; owner identifies which cloud server the resource belongs to; and price denotes the re- source's cost, which is randomly generated using a normal distribution at model startup.

Considering the resource substitution strategies developed in this paper in the face of resource failure (see Section 5.2 for details), it is necessary to continue expanding the attributes of cloud resource agents:

$$RA=RA0+\langle replace\_Resource, replace\_Rate\rangle \quad (3)$$

where replace_Resource specifies the alternative resource type Rj for each resource type Ri, with this model assuming that Ri and Rj are mutually substitutive; and replace_Rate is the replacement rate (i.e., matching rate) of the replacement resource. Although the substitute resource can replace the original resource to complete the established cloud task, there is an increase in the total work time. The resource replacement rate is generated by a normally distributed random number at the time of model initialization.

Modeling of Cloud Server Agent

The primary function of cloud servers is to convey information and interact with cloud tasks. Each cloud server's resource pool has all kinds of cloud resources. The server locates the appropriate resource in its resource pool and allots it to the cloud task after receiving the "request resource" message. The server releases the associated cloud resource and adds it back to the cloud resource pool after receiving the "release resource" message. The cloud server agent can be illustrated as follows:

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In accordance with the service route of the to-be-processed order, the cloud platform integrates and adapts various cloud tasks to create structured and reliable cloud task sequences.In order to perform cloud manufacturing services, the platform imports each order into the appropriate cloud task sequence when the cloud demand set is not vacant. Based on the task type, the appropriate resources are requested from the resource pool while processing cloud tasks. After being requested, resources in an inactive state transition to a busy state. The resource is released and returned to an idle state once the assignment has been finished. Multiple entity types are present in the CMS, and numerous forms of information transmission and behavior interactions occur among entities of the same and different types. Consequently, the CMS model can be stated as follows:

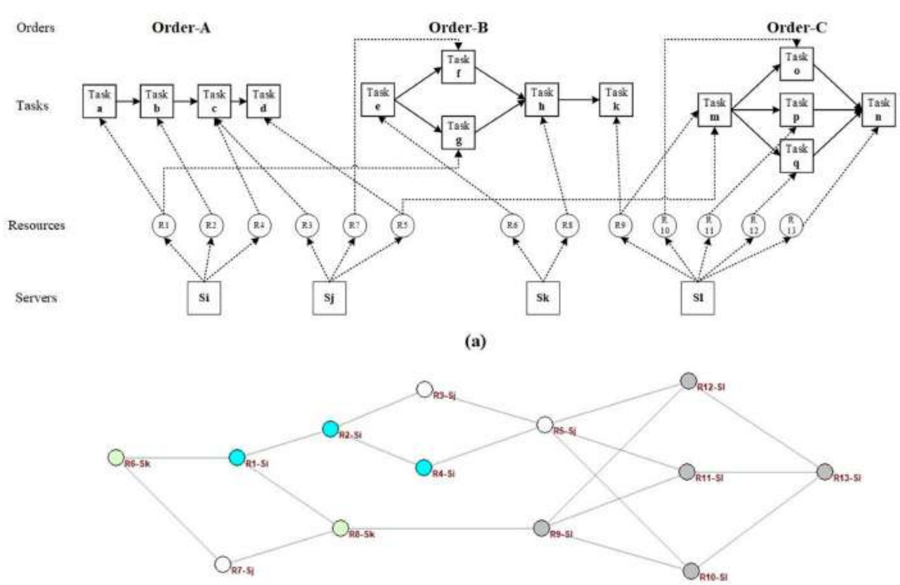
CMS={PA,DA,SA,TA,RA,OA,MA,E} (1)

where PA represents the cloud platform agent; DA represents the cloud demander agent; SA represents the cloud service agent; TA represents the cloud task agent; RA represents the cloud resource agent; OA represents the order agent issued by DA; MA represents the message agent sent to SA when TA requests or releases resources; and E represents the external environment of information transmission and inter-entity behavior interaction.

4. Model of the Cloud Manufacturing Network and Robustness Evaluation Indicator Based on Complex Network

4.1. Development of a Complex Network Model for Cloud Manufacturing

The CMN consists of cloud service resources and their interconnections. The network can be evaluated utilizing the complex network model due to the vast number of resources and intricate connection relationships. Figure 3a depicts the processing task paths for Order-A, Order-B, and Order-C, the resources utilized by each task along these paths, and the relationships between the resources and servers. If two tasks are linked by a path, their corresponding resources are also linked. Figure 3b illustrates how the CMN is formed by considering all resources to be network nodes and resource connections to be connected edges.



(a)

(b)

Figure 3. Schematic depiction of (**a**) the CMS's internal relationships and (**b**) the cloud resource network.

4.2. Evaluation Indicator for Network Robustness Based on Static Topology

The term "network robustness" is generally used to describe the degree of network performance retention following the failure of network nodes or edges, and the change in the maximum connected subgraph following node failure can reflect the degree of structural integrity retention in the network. As a result, the rate of change in the maximal connected subgraph's node count was chosen as one of the robustness evaluation indicators for this study.

5. Robust Failure Mode Definition and Formulation of Multiple Resource Replacement Strategies

5.1. Definition of Failure Modes for Robustness Analysis

The definition of failure modes is the key to robustness analysis. Based on a combination of the cloud manufacturing characteristics and the spatial topology structure of the CMN, this paper proposes two types of failure modes: cloud resource failure based on the initial topology, and cloud resource failure based on the recomputed topology.

The initial topology refers to the initial structural characteristics of the CMN, which is a static network. The recalculated topology refers to the structural characteristics of the CMN that are obtained through recalculation after the initial network is attacked, which is a dynamic network that changes step by step with the attack steps.

Both failure modes are subdivided into degree-based and betweenness-based resource failures. The degree is widely used to measure the importance of the nodes: it represents how closely a resource node is connected to other resource nodes in the CMN. The betweenness reflects the structural importance of the nodes in the network a node with high betweenness has greater control over the logistics and information flow in the network.

5.2. Formulation of Multiple Resource Substitution Strategies

Targeting the cloud resource node failure problem proposed in Section 5.1, this pa- per aims to develop a robustness enhancement strategy for CMNs that involves adding redundant nodes.

For the supply chain modeling and robustness problem, Zhao [48] took the smartphone supply chain as an example and put forward three different robustness optimization strategies: enterprise internal operation management, cooperative management between enterprises, and a regional development strategy. Inspired by this, and combined with the characteristics of cloud manufacturing, this paper proposes three kinds of robustness improvement strategies: internal resource replacement, external resource replacement, and internal–external integration replacement.

(1) Internal replacement strategy: The cloud service provider Si will internally provide replacement resources Rj for Ri (noted as Ri-Si and Rj-Si, respectively). If Ri-Si fails, Rj-Si will replace it to complete the processing of cloud manufacturing tasks. Although the tasks will be completed, the cloud task time will be increased due to the different resource types, and additional working hours will be incurred.

(2) External replacement strategy: The cloud service provider Sj, Sk . . . etc. will provide the same type of resources Ri as Ri-Si (recorded as Ri-Sj, Ri-Sk . . . etc.). When the resource Ri fails, the strategy will comprehensively select the best cloud service provider based on multiple factors, such as resource quotation and the distance between service providers. It will then request alternative resources from them to replace the failed Ri-Si to complete the cloud manufacturing task. Since the resource types are the same, this does not add additional task time; however, the transfer of resources and information among different service providers will

International Journal of Multidisciplinary Engineering in Current Research
ISSN: 2456-4265, Volume 6, Issue 5, May 2021, http://ijmec.com/

generate additional logistics transportation costs and time.

(3) Internal–external integration replacement strategy: This strategy is the combination of the previous two strategies. When a cloud resource fails, this strategy first looks for a replacement resource within the service provider; if no replacement resource is found or its replacement resource also fails, it continues to seek the same type of resource from other service providers. The logical flow of these three strategies is shown in Figure 4.

In addition, in the complex network model, node failure is reflected by removing the failed resource node and all the edges connected to the node. After selecting the corresponding resource replacement strategy, the optimal alternative resource node under the current strategy is first determined. If this replacement node is already in the original network, all connected edges belonging to the failed node will be directly linked to the replacement node; if it is not already in the original network, the replacement node should first be added to the network, then be linked similarly.

1. Case Study

1.1. Model Parameters Description

The cloud manufacturing project for a new energy vehicle is used as a case study. This project offers life-cycle cloud manufacturing services for new energy vehicles, with the technologies provided including electrification and autonomous driving.

The cloud manufacturing project consists of 24 order types, 95 cloud tasks (t1–t95), and 72 resource types (r1–r72). Table 2 displays the appropriate resource types for each cloud task, and Table 3 displays the routes for each order type's associated cloud task. This paper assumes a bidirectional substitution relationship between resources (e.g., if the substitute resource of r_i is r_j, the substitute resource of r_j is r_i). Based on this, the substitution relationships among internal resources are shown in Table 4.

Each of the project's five cloud servers (S1-S5) offers 72 different kinds of cloud resources. The cloud servers compete for different orders because they charge different prices for their resources and are located at various distances from cloud demanders. Resource r1 of servers S1–S5 are identified by the labels r1–S1, r1–S2, r1–S3, r1–S4, and r1–S5, respectively.

Moreover, there are 14 cloud demanders (d1–d14). Each cloud demander submits 24 orders, with 1 of each order type submitted (i.e., 1 of each of the 24 order types). As indicated in Table 5, the fundamental details of each cloud service provider and cloud demander are externally imported from Excel.

2. Conclusions

This study combined the complex network with multi-agent simulation to propose a new analysis method for the structural robustness and process robustness of the CMS. To target the frequent failure of resource nodes in the cloud manufacturing environment, three resource substitution strategies were proposed to better ensure the stability and robustness of the system. First, a multi-agent simulation model was constructed to study the dynamic process robustness of the CMS. Here, RoS was proposed as a robustness measure, and the behavior characteristics and modeling methods of several key types of CMP agents were detailed. Second, a complex network model of cloud manufacturing resources was established through the order–task relationship and task–resource relationship to study the static topological robustness of the CMS. Here, the maximum connectivity subgraph was proposed as a robustness measure. Regarding attack strategies, four failure modes (i.e., ID, IB, RD, and RB) were defined, and regarding robustness enhancement strategies, three resource substitution strategies (i.e., internal replacement, external replacement, and internal–external integration replacement) were proposed. Third, a case study of a cloud manufacturing project of a new energy vehicle was conducted. The results of this show that

(1) the proposed RoS index was effective at portraying the variations of CMP robustness,

(2) the three resource substitution strategies could improve both the structural robustness and process robustness of the CMS (with the internal–external integration strategy being most effective, followed by the external substitution strategy, and then the internal substi- tution strategy), and (3) the two node failure modes based on the recalculated topology were more destructive to the robustness of the CMP than the two node failure modes based on the initial topology. However, for all four failure modes, all three resource substitution strategies could protect the robustness of the CMS to some degree.

In combining the complex network with multi-agent simulation, the robustness anal- ysis object of the CMS is extended from the CMN to the CMP, which provides a new perspective with two dimensions (i.e., structure and process). Moreover, the three proposed recovery strategies (elastic measures) are designed based on the idea of adding redundant nodes, which is of great significance to the implementation and deployment of cloud man- ufacturing projects. This research will be furthered by investigating the robustness of cloud path interruption, cloud logistics interruption, city lockdowns, and other phenomena, to provide a quantitative and dynamic decision-making basis for improving the robustness of the CMS.

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