# Topological Structure and Vulnerability of Cloud Manufacturing Network

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**Abstract:** Cloud manufacturing is a new service-oriented, customer-centric and demand-driven manufacturing paradigm, which provides secure, reliable, and high quality on-demand services at low prices for those involved in the whole manufacturing lifecycle. Cloud manufacturing can provide enterprises with competitive advantage, and the vulnerability of manufacturing network may also lead to new risks. In this paper we analyze the topological structure and vulnerability of cloud manufacturing network, study the impact of topological structure on vulnerability, and propose recommendations for governance of vulnerability.

In the past two centuries, manufacturing industry has experienced many paradigms: Craft Production, American System, Mass Production, Lean Manufacturing, Mass Customization and cloud manufacturing [1, 2]. It can be considered that the early four manufacturing paradigms are production-oriented, while the latter two are customer- and service-oriented. The differences between the paradigms are reflected in the relationships of volume, variety, and cost [3]. Craft Production, as the first paradigm, is time-consuming and costly. Standardized Production of standardized parts for arms, also known as the “American System”, is the truly began of production systems. The real modern manufacturing begins with Mass Production, which enables the making of products at lower cost and high speed, but very limited variety. Lean Manufacturing, emerged after World War II in Japan, means to eliminate “waste” on all levels. Justin-time, quality systems, work teams, cellular manufacturing are all the concepts of Lean Manufacturing. Mass Customization, came up in the late 1980’s when the customers demanded more product variety, requires manufacturing systems more flexible and smarter. Cloud manufacturing is a new paradigm that has developed over the past 10 years with some new technologies [3, 4].

Cloud manufacturing is a new service-oriented manufacturing paradigm, which utilizes the network and cloud manufacturing service platform to organize manufacturing resources on the network (manufacturing cloud) according to users’ needs and provide users with various on-demand manufacturing services [5]. Cloud manufacturing technology integrates existing networked manufacturing and service technologies with cloud computing, cloud security, high performance computing, Internet of Things and other technologies, realizes unified and centralized intelligent management and operation of various manufacturing resources (manufacturing hardware, computing systems, software, models, data, knowledge, etc.), and provides secure, reliable, and high quality on-demand services at low prices for those involved in the whole manufacturing lifecycle [6].

Cloud manufacturing can provide enterprises with competitive advantage, and its vulnerability may also lead to new risks [7]. Some of these risks come from technology, and more from society. In the past two years, the international trade war has tended to escalate. This will increase the risk of cross-border cooperation among enterprises and increase the uncertainty of cloud manufacturing networks. In this context, it is undoubtedly of great practical significance to study the vulnerability of cloud manufacturing networks.

The purpose of this paper is to analyze the topological structure and vulnerability of cloud manufacturing network, study the impact of topological structure on vulnerability, and propose recommendations for governance of vulnerability.

## 1. Characteristics of Cloud Manufacturing Network

The earliest application of complex network is aimed at the Internet network with a large number of nodes, which gradually extends to the complex network with a large number of nodes, such as power network, social network, virus transmission network, etc., and then to the relatively small number of nodes such as aviation network, subway network and chemical production network [8]. Cloud manufacturing network is composed of enterprises, so the number of network nodes is relatively small.

Compared with other complex networks, cloud manufacturing network has some noteworthy topological characteristics. Firstly, Cloud manufacturing network consists of heterogeneous nodes with certain autonomy. Most of the complex networks constructed by the existing research are composed of homogeneous nodes, such as aviation network, subway network and so on. Generally, network connectivity is used to measure network performance, and a single node loses its significance after leaving a specific amount of network. In the cloud manufacturing network, enterprises provide heterogeneous products or services for the network. In addition to being members of the network, enterprises also have certain independent management capabilities.

Secondly, Cloud manufacturing networks consist of a variety of undirected and directed edges. In the study of typical complex networks, edges have relatively simple meanings, generally representing only one kind of connection and pointing to fixed, such as Internet, protein network, undirected network, scientific citation network, aviation network, etc. In cloud manufacturing network, there are many cooperative relationships among enterprises, such as technology, materials, information and so on. Therefore, edge also represents a variety of links among enterprises. Among them, the exchange of technology and materials is directional, while the exchange of information is undirected. Therefore, edges in cloud manufacturing networks are relatively more complex.

Thirdly, Cloud manufacturing is a kind of dynamic network. The typical complex networks studied in the past are relatively less disturbed, and the network structure is relatively stable, while the cloud manufacturing network has many disturbing factors, including government policies, market environment, operating conditions, etc. When disturbed by internal and external factors, the network structure is prone to change. Therefore, compared with typical complex networks, cloud manufacturing networks have stronger dynamic characteristics.

## 2. Vulnerability of cloud manufacturing network

Each enterprise in cloud manufacturing is regarded as a network node. $V = \{v_1, v_2, v_3, \ldots, v_n\}$ is the node set of networked manufacturing network and n is the number of node. $R = \{r_1, r_2, r_3, \ldots, r_n\}$ is the relationship set of the nodes. $R_{i,j}$ is the relationship set from $v_i$ to $v_j$.

Considering the relationship between $v_i$ and $v_j$ as the directed edge of the network, the adjacency matrix is constructed as $E_{n\times n} = [e_{i,j}]$. $e_{i,j} = 1$ if $R_{i,j} \subseteq R$, which means that there is directed edge $\langle v_i, v_j\rangle$ between $v_i$ and $v_j$. Otherwise $e_{i,j} = 0$. $m = \sum e_{i,j}$ is the number of edges contained in cloud manufacturing network. In this way, cloud manufacturing network can be expressed as $G\langle V, E\rangle$, which is composed of the nodes and the edges.

The vulnerability of a system refers to the nature of the impact on the overall system function after the failure of system components. Therefore, the study of system vulnerability is to correctly evaluate the vulnerability of the system, identify the key nodes and weak links that affect the vulnerability of the system, and take effective measures to reduce vulnerability and improve invulnerability [9].

The vulnerability of cloud manufacturing refers to the impact of the failure of cooperation among some enterprises on the whole manufacturing network. Based on the vulnerability analysis principle of complex network theory, vulnerability S of cloud manufacturing network is defined as:

$$S[G,D] = \frac{\Phi[G] - W[G,D]}{\Phi[G]} \tag{1}$$

D is the set of attacks that network G may be attacked. D (G, d) denotes the network after G is attacked by $d \subseteq D$. The proportion of network function decline $\triangle\Phi^- / \Phi$ denotes the severity of attack d, that is, the vulnerability of the network, $\triangle\Phi^- = \Phi[G] - \Phi[D(G,d)] \geq 0$. When $\Phi[D(G,d^*)]$ is the minimum, $\triangle\Phi^-$ is the maximum, then $d^* \subseteq D$ is the most serious attack. Among them, $W[G,D] = \Phi[D(G,d^*)]$, and S[G, D]∈[0, 1].

The main characteristics of complex networks are heterogeneity, node centrality, scale-free and small-world. In the analysis of network topology structure, as long as one of the characteristics is satisfied, the network can be considered to have complex network characteristics.

In the analysis of complex networks, the commonly used network metrics mainly include connectivity, clustering coefficient, toughness and so on. Different metrics can reflect the different characteristics of network structure and nodes. However, these indicators are not the best indicators to measure the network function of networked manufacturing projects [10].

We introduce the network efficiency based on the strength of the relationship between nodes as the index to measure the network function. In a weightless network, the strength of the relationship between nodes is inversely proportional to the shortest path. If the average strength of the relationship between nodes is taken as the network efficiency E (G),

$$E(G) = \frac{\sum_{i \neq j} \varepsilon_{i,j}}{n(n-1)} = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{l_{i,j}} \tag{2}$$

$\varepsilon_{i,j} = 1/l_{i,j}$, which denotes the strength of the relationship between node $v_i$ and node $v_j$. $\varepsilon_{i,j} = 0$ means that there is no path between the two nodes; $\varepsilon_{i,j} = 1$ means that the two nodes are directly connected; otherwise, $0 < \varepsilon_{i,j} < 1$。

When the network is attacked, whether the node fails or the edge fails, the strength of the relationship between the nodes will change, which will affect the efficiency of the network. Therefore, network efficiency can be used to measure the network function of networked manufacturing projects comprehensively and accurately.

## 3. Impact of Topological Structure on Vulnerability

The main topological parameters of cloud manufacturing network are node degree, node median, edge degree and edge median. Node degree denotes the number of directed edges associated with node $v_i$. Node degree in the directed graph is the sum of the outgoing degree and the entry degree of the node,

$$k_v(i) = \sum_j \left(e_{i,j} + e_{j,i}\right) \tag{3}$$

Node median is the ratio of the number of shortest paths passing through the node to the number of all shortest paths in the network,

$$b_v(i) = \frac{1}{(n-1)(n-2)} \sum_{s \neq i \neq t} \frac{g_{s,t}(i)}{g_{s,t}} \tag{4}$$

Edge degree denotes the number of edges associated with the edge. We use the product of the nodal degrees to represent edge degree,

$$\mathrm{k_e(i,j) = k_v(i) \cdot k_v(j)} \tag{5}$$

Edge median is the ratio of the number of shortest paths passing through the node to the number of all shortest paths in the network,

$$b_e(i,j) = \frac{1}{2(m-1)} \sum_{e_{i,j} \neq e_{s,t}} \frac{\delta_{s,t}(i,j)}{\delta_{s,t}} \tag{6}$$

In order to study the relationship between network vulnerability and node degree, node median, edge and edge median, we made simulation analysis. The results show that network vulnerability is positively correlated with node degree and node median, and is not significantly correlated with edge degree and edge median.

Further analysis shows that the network vulnerability caused by the simultaneous failure of two nodes is greater than the sum of the vulnerability values when two nodes fail respectively.

## 4. recommendations for governance of vulnerability

Cloud manufacturing is generally a complex network, which is dominated by one or several core enterprises and expanded layer by layer according to actual demand and market environment. The vulnerability of cloud manufacturing network is mainly caused by the withdrawal of enterprises or the breakdown of cooperation among enterprises [11]. We propose the following recommendations for governance of vulnerability in view of the different impacts and capabilities of nodes and edges on network vulnerability.

Firstly, Core companies should pay more attention to the stability of partner companies. The partner companies in cloud manufacturing are all capable of independent operation, so they have strong autonomy in the process of cooperation. When a company is affected by many factors such as the market environment and policy environment, it may exit the manufacturing network. Therefore, core companies should pay more attention to the stability of partner companies in selecting partners and subsequent cooperation, especially to those that have important impacts on other enterprises in the network. This is actually a very difficult task due to the complexity of the manufacturing network [12].

Secondly, It is necessary to avoid the simultaneous failure of network nodes which can bring greater vulnerability. The simulation results show that the network nodes with simultaneous failure will magnify the vulnerability of the network. Therefore, the core enterprises of cloud manufacturing should not only pay attention to the operating status of each partner company, but also prevent multiple companies from failing at the same time. Especially when there is a company failure in the network, it is necessary to ensure the normal operation of the relevant companies to reduce the overlapping effect of vulnerability.

Thirdly, Core companies should constantly evaluate the vulnerability of cloud manufacturing networks. When a partner company launching a manufacturing network, or a new company joining the manufacturing network, the vulnerabilities of the nodes will also change. So, the core company should dynamically evaluate the vulnerability of the cloud manufacturing network. If the vulnerability of the network node is too large, or more than one partner companies cannot fulfill their responsibilities or launch the manufacturing network at the same time, it is necessary to take corresponding measures to prevent the network from collapsing.

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