Modeling and Characteristic Analysis of Manufacturing Enterprise Collaboration Network for Complex Product

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Abstract. In order to meet the requirements of customers for complex products quickly, manufacturing enterprises begin to collaborate with other enterprises, and in the cooperation, the service relationships between enterprises by providing products to others shape the manufacturing enterprise collaboration network (MECN). With the increase of MECN scale and cooperation closeness among enterprises, it is necessary to analyze the performance of MECN to ensure the stability of cooperation. In this paper, MECN is modeled by partner selection of multiple enterprises using entropy and TOPSIS method, and based on the model, the topology characteristics and vulnerability of MECN are analyzed by using of complex network theory. A case study of automobile engine cooperation manufacturing network is provided to illustrate our work, and the results show that the MECN of automobile engine exhibits the small-world property; and by analysis the vulnerability of the network, the critical enterprise nodes can be identified for failure prevention.

1. Introduction

With the increasing demand for products and rapid development of science and technology, the number and complexity of complex products are rising sharply, so a large number of enterprises cooperate with others to improve their competitiveness. For example, automobile products, including thousands of parts, cannot be completed by a single enterprise, usually done jointly by a number of enterprises. In the cooperation, the service relationships between the enterprises by providing products to others shape the manufacturing enterprise collaboration network (MECN) [1]. In this kind of network, manufacturing enterprises only guarantee core businesses or parts, and other businesses or parts are outsourced or purchased, so as to meet the market demand through the lower cost and faster response.

With the development of society and technology, as well as the specialization of manufacturing division, the scale of MECN is increasing, and the collaboration between enterprises is more closely. Therefore, the modeling and analysis for MECN is more important. Because a single enterprise's behavior or failure will affect its neighboring enterprises, and ultimately increase the risk of failure of the whole collaboration network.

The premise of modeling and analysis for MECN is to select the suitable partners from a number of potential suppliers, so as to determine the enterprise nodes of the network. Many scholars have studied the partner selection problem. Generally, there are three types of methods for partner selection: mathematical programming approach [2,3], intelligent algorithm [4,5], and uncertainty theory [6-8]. These three methods have their own advantages and disadvantages. The mathematical programming method can get the exact solution of the problem, the intelligent algorithm is suitable for solving the
large-scale complex problem, and the uncertainty theory is simple and easy to implement, which is also the most widely applied method in practice. Therefore, in this paper, entropy method and TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) are used together to solve the partner selection problem. The entropy method is used to determine the weight of each attribute index of suppliers, and TOPSIS is adopted to evaluate the performance of each supplier. Finally, the combination of the two methods can help manager to select the supplier with the best performance.

When the supplier for each part of the complex product is determined, the MECN is constructed, and the performance of the MECN can be analyzed further. As collaboration network, MECN can be analyzed with the complex network theory, and many researches have begun to use complex network theory to describe and analyze complex manufacturing problems [9]. For example, the model of aircraft cooperation manufacturing network is established by Peng and Meng [1], and it is demonstrated that this network has the characteristics of self-organization, complexity and localization. Cheng et al. [10] put forward the supply–demand matching hypernetwork of manufacturing services to describe the service-oriented manufacturing systems. Li et al. [11] studied the relationship of supplier cooperation strategy and topology structure of supply chain network, and proved that heterogeneous network is more beneficial for promoting cooperation. Tao et al. [12] analyzed the composition service network and proved that it has scale-free characteristics.

It can be seen that complex network theory can be used to describe the system and reveal the characteristics of system through topology analysis. However, at present, research on MECN by using of complex network theory is not much and further work is needed, especially the research for network performance, such as the vulnerability analysis. Although enterprises have gained competitive advantage through cooperation, they are also facing new risks, such as the failure of some enterprises will affect their cooperation enterprises, and even affect the normal operation of the entire cooperation network, finally increasing the vulnerability of the network [13]. Therefore, it is necessary to find the important enterprise nodes that affect the network vulnerability so as to ensure the normal operation of the network.

In this paper, we construct MECN by partners selection from multiple enterprises with entropy and TOPSIS method, and based on the model, the topology characteristics and vulnerability of MECN are analyzed from the perspective of complex network. The rest of this paper is organized as follows: Section 2 explains the construction process of MECN. An application about automobile engine-related MECN is introduced in Section 3. Finally, conclusions and future work are summarized in Section 4.

2. Modeling Process of MECN for Complex Product

The model of MECN is based on the manufacturing process of a particular complex product. The product is made up of thousands of parts which are partly made by the manufacturer itself, and most of them are provided by many other enterprises. Therefore, the MECN is the description of supply-demand relationship between the enterprises. The modeling process of MECN for complex product is shown in Figure 1, and mainly contains 4 steps as follows:

(1) Structural decomposition of complex product: choose a complex product, and break down the product into different parts to obtain the product structure tree.
(2) Find potential suppliers: find the potential suppliers for all parts and construct supplier set of each part. In this paper, the self-made parts are provided by the manufacturing enterprise itself, and the outsourcing parts are supplied by other enterprises.
(3) Partner selection: from each supplier set of outsourcing part, select the supplier with the best comprehensive performance as the partner by using of entropy and TOPSIS method, then the enterprise nodes of the MECN can be determined.
(4) MECN formation: according to the top-down matching relationship of part pairs, the relationship between the partner enterprises can be determined, and the MECN is shaped.
2.1. Partner Selection

In this paper, TOPSIS is adopted to select the partner with best comprehensive performance from multiple potential suppliers for each outsourcing part, and entropy method is used to determine the weight of each evaluating index of the suppliers.

Suppose, there are $n$ potential suppliers for each outsourcing part, and evaluating indexes include $k$, where $x_{ij}$ represents the value of index $j$ ($j = 1, 2, \ldots, k$) in supplier enterprise $i$ ($i = 1, 2, \ldots, n$). The procedure of partner selection is as follows:

1. **Assimilate the indexes.** Aimed at these indexes, transforming the optimal index with low value into high index as follows:

   $$ x_{ij}^{'} = \begin{cases} x_{ij}, & \text{high index} \\ 1/x_{ij}, & \text{low index} \end{cases} $$

2. **Normalize the indexes.** In order to directly compare the indexes with different dimension and magnitude order, there is need to normalize the values of each index after assimilation. The normalization method is as below, and then the normalized matrix $Y$ can be obtained.

   $$ y_{ij} = \begin{cases} x_{ij}^{'} / \sqrt{\sum_{t=1}^{k} (x_{ij}^{'})^2}, & \text{high index} \\ x_{ij}^{'} / \sqrt{\sum_{t=1}^{k} (x_{ij}^{'})^2}, & \text{raw low index} \end{cases} $$

Figure 1. Modeling process of MECN for complex product.
(3) determine the weight of each index by using of entropy method. Firstly, calculate the information entropy of each index by formula \( E_j = -\ln(n) \sum_{i=1}^{n} p_{ij} \ln p_{ij} \), where \( p_{ij} = y_{ij}/\sum_{i=1}^{n} y_{ij} \), and if \( p_{ij} = 0 \), then \( \lim_{p_{ij} \to 0} p_{ij} \ln p_{ij} = 0 \); next calculate the weight of each index and obtain weight vector \( W = \{w_1, w_2, \ldots, w_k\} \), where \( w_j = (1 - E_j) / (k - \sum_{j=1}^{k} E_j) \); then the normalized matrix after weighted processing can be obtained as follows:

\[
Z = W \times Y = \\
\begin{bmatrix}
w_{1}y_{11} & w_{1}y_{12} & \cdots & w_{1}y_{1k} \\
w_{2}y_{21} & w_{2}y_{22} & \cdots & w_{2}y_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
w_{k}y_{k1} & w_{k}y_{k2} & \cdots & w_{k}y_{nk}
\end{bmatrix}
\]

(4) determine the best index and the worst index. The optimal index \( Z^+ \) is composed of the maximum values in each column in the matrix \( Z \), that is \( Z^+ = (\max z_{1i}, \max z_{2i}, \ldots, \max z_{ni}) \), where \( i = 1, 2, \ldots, n \). While the worst index \( Z^- \) is composed of the minimum values in each column in the matrix \( Z \), that is \( Z^- = (\min z_{1i}, \min z_{2i}, \ldots, \min z_{ni}) \), where \( i = 1, 2, \ldots, n \).

(5) calculate the distance \( D^+_i \) and \( D^-_i \) of each index with the best index \( Z^+ \) and the worst index \( Z^- \), where

\[
D^+_i = \sqrt{\sum_{j=1}^{k} (\max z_{ij} - z_{ij})^2}, \quad D^-_i = \sqrt{\sum_{j=1}^{k} (\min z_{ij} - z_{ij})^2}.
\]

(6) calculate the proximity of each index with the best index by formula \( C_i = D^-_i / (D^+_i + D^-_i) \), where \( 0 \leq C_i \leq 1 \), and the closer the value of \( C_i \) to 1, the better the evaluation object.

(7) according to the values of \( C_i \), the evaluation results are given. Finally, the supplier with the maximum value of \( C_i \) is selected as the partner.

2.2. MECN Formation

The model of MECN can be described as follows: \( G=(V,E) \), while \( V = \{v_1, v_2, \ldots, v_n\} \) is the enterprise node set representing the manufacturing enterprise and its partners; \( E = \{(v_1,v_2), (v_2,v_3), \ldots, (v_{k},v_{k})\} \) is the edge set representing the supply-demand relationship between enterprise nodes. Based on the product structure tree, the enterprise node set \( V \) and the relationship set \( E \) between nodes and nodes are formed in the process of supplier selection as shown in Figure 2.

![Figure 2. The formation process of MECN.](image)
The formation process of MECN mainly includes 5 steps as follows:

1. **Information initialization**: including setting up the part identifier and its self-made or outsourcing attribute matrix, parent-child relationship matrix, supplier attribute matrix, part-supplier relationship matrix, and adjacency matrix for the network. All of these are shown in Figure 3. In the initialized information as shown in Figure 3, the part ID and supplier ID are both the unique identification; the 0/1 attribute of the part represents self-made or outsourcing respectively; for each supplier, there are 7 attribute indexes to be considered, including on-time delivery, total contribution last year, managerial assessment, average delays last year, adequate quality last year, rejected order last year, and frequency of selection last year, and the average delays and rejected orders are negative indexes; and for the adjacency matrix of the network, set \( A = \{ a_{ij} \} \), where \( a_{ij} = 0, 1 \leq i, j \leq n \).

2. **Scanning the parent-child relationship matrix**: to judge the 0/1 attribute of each part, if it is a self-made part, then set up its supplier as 0 to represent the manufacturer itself, and if it is an outsourcing part, then go to the next step.

3. **Combining the values in the supplier attribute matrix**: to select the best partner from multiple potential suppliers for each outsourcing part by using the TOPSIS and entropy method.

4. **According to the parent-child relationship**: set up the element in the adjacency matrix as \( a_{ij} = 1 \), it means the cooperation relationship between the supplier enterprises for parent-child parts.

5. **Repeat the steps (2)-(4) until the scanning is completed**: finally, the MECN is formed according to the adjacency matrix A obtained.

### 3. Case Study

Automobile is a typical complex product and includes thousands of parts. In order to meet the needs of customers quickly, automobile manufacturers must establish cooperation with other enterprises. In this paper, the core component of an automobile, a type of engine, is taken as an example to construct and analyze the MECN.

#### 3.1. MECN Formation

1. **Initial information generation**

   This automobile engine is composed of hundreds of parts, and 201 main parts are selected to form the product tree of the engine as shown in Figure 4. In Figure 4, the letter Z represents the self-made part, and G represents the outsourcing part. There are 174 outsourcing parts and 27 self-made parts.
According to the product structure tree of the engine, the part information and parent-child relationship between the parts can be obtained. In addition, the part-supplier relationship and the attribute values of each supplier are obtained from the supplier management system of the company. In this paper, considering 5 suppliers for each outsourcing part, and there are 100 suppliers totally.

**Figure 4. Structural decomposition of automobile engine (typical parts).**

(2) Partner selection and network formation

According to the process of supplier selection as shown in Figure 2, the adjacency matrix A representing the relationship of manufacturer/suppliers can be obtained. In the adjacency matrix, the isolated nodes mean that these enterprises are not selected as partners. After deleting these solitary nodes, the MECN structure for the automobile engine is shown in Figure 5 with the aid of Ucinet software. As can be seen from Figure 5, there are 96 nodes in total, and all of the nodes are connected with other nodes; and some of nodes are associated with many other nodes, it means that these enterprises can provide a variety of types of parts.

### 3.2. Characteristics Analysis of MECN for Automobile Engine

For complex network, the network characteristics are usually analyzed with node degree, clustering coefficient and average path length.
(1) Degree distribution

Degree distribution is an important parameter to measure the network. The degree $K_i$ of a node $i$ represents the number of edges connected with other nodes. It is defined as follows:

$$K_i = \sum_{j=1}^{N} a_{i,j}, \text{ where } a_{i,j} = \begin{cases} 1, & \text{node } i \text{ is connected with node } j \\ 0, & \text{otherwise} \end{cases}$$

(1)

Generally, the greater the degree, the more important the node is in the network. The degree distribution of MECN for automobile engine is shown in Figure 6. It can be seen that most of the nodes in this MECN have low degrees, while a small number of nodes have relatively high degrees, because some of the suppliers can provide a variety of parts at the same time, and they are also the key nodes.

(2) Clustering coefficient

Clustering coefficient is a measure of the collectivization degree of the network, representing the connecting relationships between the neighbors of a node. In a network, $K_i$ is the degree of node $i$, and $E_i$ means the edge number among the neighbors of node $i$, while $K_i(K_i-1)/2$ is the all possible connection edges among the neighbors of node $i$. The clustering coefficient of node $i$ is calculated as follows:

$$C_i = \frac{E_i}{K_i(K_i-1)/2} = \frac{2E_i}{K_i(K_i-1)}$$

(2)

The clustering coefficient of the network is defined as follows:

$$C = \frac{1}{N} \sum_{i=1}^{N} C_i$$

(3)

Where, $0 \leq C \leq 1$, and the closer the value of $C$ is to 1, the higher the network aggregation degree.

(3) Average path length

Average path length is another important characteristic of network. The distance $d_{ij}$ between nodes $i$ and $j$ in the network is defined as the number of edges along the shortest path between them. The average path length of the network is defined as the average value of the distance between any two node pairs, given by:

$$L = \frac{1}{2N(N-1)} \sum_{i,j} d_{ij}$$

(4)

For the MECN of automobile engine, by using of the Ucinet software, the average degree $K$, average clustering coefficient $C$, and average path length $L$ are calculated, and the comparison results with
random network are shown in Table 1. For random network, the average clustering coefficient is $C_r \propto K / N$, and average path length $L_r \propto \ln(N) / \ln(K)$.

**Table 1.** Comparison between MECN of automobile engine and random network.

| Node number $N$ | Average degree $K$ | Average path length of MECN $L$ | Average path length of random network $L_r$ | Average clustering coefficient of MECN $C$ | Average clustering coefficient of random network $C_r$ |
|-----------------|--------------------|-------------------------------|-----------------------------------------------|------------------------------------------|-----------------------------------------------|
| 96              | 3.771              | 3.227                         | 3.439                                         | 0.172                                    | 0.039                                         |

From Table 1, it can be seen that $C \gg C_r$, and $L \approx L_r$, which shows that the average clustering coefficient of the MECN of automobile engine is far greater than that of random network, while the two networks have similar short average path length. From the comparison results, it can be concluded that the MECN of automobile engine has the characteristics of small world, and this type network has a high fault tendency.

(4) **Vulnerability**

The vulnerability of network is a measure of the impact of the failure of a single or part of the nodes on the whole network, and network efficiency is often used to evaluate the overall performance of the network. Therefore, vulnerability of the MECN can be measured by comparing the network efficiency before and after failure of node. Network efficiency is calculated as follows:

$$\varepsilon = \frac{1}{N(N-1)} \sum_{i,j \in \mathcal{N}} 1/d_{ij}$$  \hspace{1cm} (5)

The value of network efficiency $\varepsilon \in [0,1]$ indicates the quality of network connectivity, and the higher the network efficiency is, the better the connectivity of the network; and $\varepsilon = 1$ means that the connectivity of the network is best, while $\varepsilon = 0$ shows that the network is composed of isolated nodes. In this paper, the simulation experiment is carried out by deleting each node in the network, and the changes of the network efficiency before and after the node destruction are calculated to quantify the importance of each node. If a node is deleted, and the change of the network efficiency, i.e., $\Delta \varepsilon = \varepsilon - \varepsilon_0$, is bigger, then it indicates that the impact of the node on the MECN is greater, and this node is the weak node in the network which needs special protection.

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In Figure 7, it is the changes of the network efficiency before and after deleting each node in the MECN. The rhombus line represents the initial network efficiency of the network, and the dot line is the corresponding network efficiency after the deletion of each node.

![Figure 7. Efficiency of MECN before and after node failure.](image-url)
From Figure 7, it can be seen that only a few of nodes fail, the efficiency of the network changes greatly, on average, the final efficiency remains a high value in most of time. It shows that the failure of most enterprise nodes will not have an important impact on the MECN, but for some specific enterprises, it is necessary to attach great importance to them, because once parts cannot be available on time from these enterprises, it will affect the efficiency of the whole manufacturing. For example, the node 1 representing the manufacturer itself, it has the greatest impact on the network, because the manufacturer itself bears the self-made work of 27 parts of the engine. In addition, the suppliers corresponding to node 32 and node 91 have greater impact on the network.

4. Conclusions
In this paper, the method of modeling and characteristic analysis of MECN for complex product is researched. The MECN is formed by partners selection from multiple enterprises with entropy and TOPSIS method, and the characteristics of MECN is analyzed using complex network theory. A case study about automobile engine-related cooperation manufacturing network is studied, and the results reveal that the MECN of automobile engine exhibits the small-world property, and the safety performance of the MECN is affected by some nodes with bigger changes of network efficiency. In a word, the developed method in this paper is a simple and effective method to model and analysis MECN, and it can help manufacturing enterprises to have deeper understanding of MECN and manage suppliers more efficient. Future work will be orientated to research the effect of one node failure on other nodes, and the control of failure propagation.

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