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Supply Chain Collaboration Degree of Manufacturing Enterprises Using Matter-Element Method

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Abstract
Evaluation of the collaboration of the upstream and downstream enterprises in the manufacturing supply chain is important to improve their synergistic effect. From the supply chain perspective, this study establishes the evaluation model of the manufacturing enterprise collaboration on the basis of fuzzy entropy according to synergistic theory. Downstream enterprises carry out coordinated capital, business, and information flows as subsystems and research enterprises as composite systems. From the three subsystems, the collaboration evaluation index is selected as the order parameter. The compound fuzzy matter-element matrix is established by using its improved algorithm. Subordinate membership and standard deviation fuzzy matter-element matrixes are constructed. Index weight is determined using the entropy weight method. The closeness of each matter element is then calculated. Through a representative of the home appliance industry, namely, Gree Electric Appliances Inc. of Zhuhai, empirical analysis of data in 2011–2017 from the company and its upstream and downstream enterprise collaboration shows a good trend, but the coordinated development has not reached stability. Gree Electric Appliances Inc. of Zhuhai need to strengthen the synergy with upstream and downstream enterprises in terms of cash, business, and information flows to enhance competitiveness. Experimental results show that this method can provide precise suggestions for enterprises, improve the degree of collaboration, and accelerate the development and upgrading of the manufacturing industry.

Keywords
Collaboration Degree Evaluation, Fuzzy Matter Element, Supply Chain

1. Introduction

With the intensification of competition in the global market, the competition amongst enterprises has been transformed into the confrontation between the supply chain and its overall strength. The key link of the supply chain is whether the upstream and downstream enterprises can form a highly coordinated state of mutual dependence, mutual cooperation and common growth. This concept is the embodiment of the rationality of the supply chain operation. If an enterprise wants long-term development, it must pay close attention to the changes in the external environment and make comprehensive use of internal resources. At present, more and more enterprises use external resources to establish close cooperation and mutual assistance with upstream and downstream enterprises, so as to better cope with external challenges and promote the rapid development of enterprises.

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Supply chain collaboration is a way for manufacturing industry to effectively use resources, reduce operating costs, increase profits, improve customer satisfaction and enhance competitive advantage. It is highly concerned by most managers, and many researchers have done a lot of research on supply chain collaboration. Lummus et al. [1] listed supply chain collaboration evaluation indicators from four aspects, namely, supply, process management, delivery and demand management. La Forme et al. [2] established a collaborative feature model and a collaborative-oriented performance model. These models were studied using upstream, internal, downstream and inter-enterprise collaboration indicators of the supply chain. Arns et al. [3] evaluated the supply chain collaboration performance from multiple perspectives, such as operational level, profit, flexibility, reliability and cost. Chiu et al. [4] proposed a contract menu based on targeted sales rebate, order quantity and quantity discount, and discussed the coordination of the relationship between supply chain and mean-variance retailers. Pyke et al. [5] used lead time, cost, quantity and quality to measure synergies. David and Adida [6] studied the supply chain collaboration between a single supplier and multiple retailers selling products through direct channels. The author extended the quantity discount contract to supply chain coordination. Cao et al. [7] explored the effects of supply chain coordination from information sharing, goal consistency, joint decision-making, incentive alliances, resource sharing, collaborative communication and joint knowledge innovation. Liu et al. [8] focused on a specific partial refund policy, collaboration between supply chain and customer returns and stochastic demand. Ruiz-Benitez and Muriel [9] studied the influence of customer return information on supply chain coordination under wholesale prices and repurchase contracts. Raweewan and Ferrell [10] studied information sharing between upstream and downstream enterprises in a cooperative competition environment, and the authors also used game theory to explore information sharing between enterprises to provide insights for decision makers. Zhang and Cao [11] explored the influence of collaborative culture and the use of interorganizational system (IOS) in supply chain collaboration by examining arbitration mediation models. The results showed that collaboration culture directly and indirectly enhances supply chain collaboration by facilitating the use of IOS. Wu and Chiu [12] studied the effects of social capital and justice issues and technology use behaviors on the upstream and downstream synergies of the supply chain. The results showed that the use of technology has an important influence on supply chain synergies. Costantino et al. [13] studied the bullwhip effect extensively, including demand signal processing, delivery time, order quantity, and price fluctuation. It is pointed out that bullwhip effect is one of the main consequences of lack of cooperation in supply chain. They proposed that the bullwhip effect in supply chain can be reduced by using quantitative and game, and supply chain coordination ability can be improved. Wu et al. [14] believes that social interaction issues, trust, commitment, reciprocity and power affect the synergy effect of supply chain. The research shows that many existing researches focus entirely on analyzing the impact of performance on supply chain collaboration. Using contingency theory and transaction cost economics (TCE), Narayanan et al. [15] explores the relationship between collaboration, trust, and agile performance in buyer-supplier relationships. Beamon [16] established a supply chain coordination index system from both qualitative and quantitative aspects, and a supply chain coordination evaluation system from the perspective of supply chain strategic objectives. Goh and Eldridge [17] established a structural equation model from the perspective of coordination and contingency theory, which proves that strategic coordination and information acquisition/processing mechanism can improve Sales & Operation Plan (S&OP) results and supply chain performance. Alaei and Setak [18] studied the multi-objective coordination problem of supply chain with path selection by using revenue sharing contract. The model proposed by the authors takes into account the aggregate demand of each retailer, but does not explore the influence of supplier route choice on supply chain coordination. Cai et al. [19] initially assumed the presence of certainty requirements and found that the option contract can coordinate the supply chain and arbitrarily distribute the coordination profit amongst members. Studies have shown that option contracts achieve good supply chain coordination in the case of random demand. Li et al. [20] designed a negotiation-based coordination mechanism to determine the production and order planning decisions of the seller and the buyer for the supply chain planning problem under the condition of asymmetric cost and demand information. The results showed that the mechanism has a good synergistic optimization effect. Cardenas-Barron and Sana [21] studied the channel coordination problem of a supply chain composed of a retailer and a manufacturer. The authors also develop a production inventory model that takes its unit purchase cost as a function of productivity to maximize the entire supply chain and profits. Lin et al. [22] studied a modified confirming warehouse financing (CWF) model. The results showed that only the two-way compensation CWF can achieve proper supply chain coordination. Lan et al. [23] studied manufacturers' distribution of products to retailers with uncertain demand through two channels. The results show that when the level of demand uncertainty exceeds the threshold, the two-channel system is beneficial to both manufacturers and retailers, and can achieve good supply chain synergies. Jung and Song [24] studied the usage of information and knowledge sharing to facilitate supply and demand matching in trading systems.

From relevant research, we can find that most scholars have carried out simple collaboration model or correlation analysis. There are few studies from the perspective of supply chain and collaboration theory. Supply chains emphasize suppliers, manufacturers, distributors, and retailers, providing services or products to end users of end users. The coordinated development of upstream and downstream enterprises is a process involving capital, business and information flow, and each link can be used as a subsystem. Therefore, the coordinated development of upstream and downstream enterprises is of great significance to improve the overall operation efficiency of enterprises. At present, the methods used include the balanced scorecard method, the analytic hierarchy process (AHP) and the average weighted sum method, etc. However, these methods have the defects of strong subjectivity and low accuracy. In order to solve these problems, matter-element analysis and evaluation method are adopted in this work. Based on the comprehensive fuzzy theory and entropy method, an objective, reasonable and accurate evaluation model of cooperation between upstream and downstream enterprises is established. These methods are designed to avoid the influence of subjective factors on the weight of indicators.

The remaining part of this paper has been arranged as follows: the supply chain coordination mechanism of manufacturing industry is analyzed, and selects the index system that affects the supply chain coordination in Section 2. The manufacturing supply chain collaboration degree evaluation model is constructed based on matter-element algorithm in Section 3. A case study is presented in Section 4, and the conclusion is provided in Section 5.

2. Scheme Supply Chain Coordination Model and Evaluation Index for Manufacturing Enterprises

Ansoff [25] introduced collaborative thinking into management for the first time and pointed out that independent entities or systems can form cooperative groups. The formed cooperative groups can effectively show simple summaries of independent entities or systems. Haken [26] first proposed the concept of collaboration in his book, *Collaborative Science*, and established a formal discipline in collaboration. Synergistic theory indicates that a large number of independent motion and interaction subsystems are present in an open system [27-29]. When the collaboration between subsystems is weak, the system is disordered; when the synergistic effect of the subsystem reaches a certain level at the critical value, the system exhibits a stable and orderly state through a self-organization phase transition.

Synergetics is based on current scientific achievements, such as catastrophe theory, information theory, cybernetics and systems theory. Here, the collaboration between upstream and downstream enterprises in the supply chain depends on the interaction amongst various elements within each subsystem of the capital, business flow and information flows. The various elements and resources in the subsystem are rationally configured. Under the impetus of external economic conditions, such as the market, enterprises seek cooperation and development through independent means; conduct communication and exchanges in capital, technology and service; and seek mutual relations in competition. When interaction reaches a critical point, the qualitative change of the system forms a synergistic effect and enters a stable and orderly state.

2.1 Supply Chain Coordination Model for Manufacturing Enterprises

Given the particularity of upstream and downstream enterprises in the same supply chain, this study analyses the basic structure of inter-firm collaboration on the basis of synergistic theory (Fig. 1). The synergistic mechanism between enterprises is used to construct the evaluation model of collaboration between supply chain enterprises.

Collaboration occurs in the synergistic process. Synergistic effect refers to the overall or collective effect produced by a large number of subsystem interactions in an open system. The overall effect of the system may be greater than the simple summary of the benefits of each independent component, and is then called collaboration.

According to synergistic theory, this study uses capital, business, and information flows as enterprise subsystems. The enterprises make up the composite system and the technology, knowledge, and information flow between the subsystems. The result is a synergistic effect.

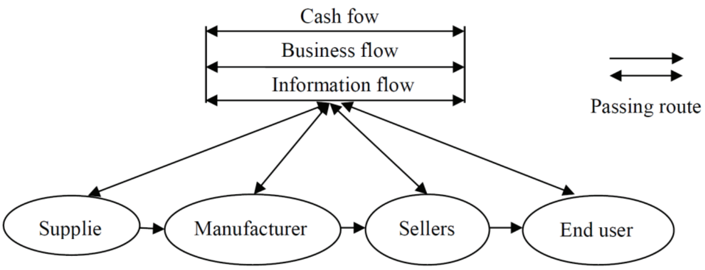

Fig. 1. Collaborative model of upstream and downstream enterprises in the supply chain.

2.2 Collaborative Order Parameter Index System of Manufacturing Enterprise Supply Chain

The order parameter is generated along with the phase change from disorder to order. Before the phase change occurs, the order parameter is zero. When the phase change occurs, the order parameter increases with the order degree of the system. The order parameters are derived from the coordination of subsystems and govern their behavior. The collaboration between subsystems generates an ordered structure, as determined by multiple order parameters working together.

This study is based on the systemic, scientific, and hierarchical principles. Previous literature presents various indicators, which are comprehensively considered in the present study on the basis of the development level of manufacturing enterprises [15-18]. Indicators with high frequency of use and data availability are selected under three categories, covering finance, product competitiveness, user satisfaction, partnerships, customer service and supply chain operational capabilities. On the basis of objectively reflecting the synergetic effect of upstream and downstream enterprises, the quantitative results also represent those of assessment. The results can fully reflect the synergy between enterprises. Thus, a representative of the home appliance manufacturing industry in China, Gree Electric Appliances Inc. of Zhuhai, is selected to carry out an example analysis. Research and analysis of the company's annual financial statements are carried out through the production, sales, and R&D departments. The original indicators and data of the order parameters are obtained to ensure that the company can represent the development of their collaboration from 2011 to 2017. The order parameter index systems of the capital, business, and information flow subsystems include 10, 8, and 3 indicators, respectively (Table 1).

Table 1. Enterprise collaboration evaluation index system

The total goal	First level index	The two level index
Evaluation of supply chain collaboration A	Capital flow B_1	Net assets income rate C_1
		Sales profit rate C_2
		Sales growth rate C_3
		Receivable turnover rate C_4
		Inventory turnover rate C_5
		Current ratio C_6
		Cash flow liability ratio C_7
		Interest guarantee multiples C_8
		Asset-liability ratio C_9
		Operating Cost Ratio C_{10}
	Business flows B_2	Product qualified rate C_{11}
		Timely delivery rate C_{12}
		Delivery accuracy rate C_{13}
		The core of enterprise production and marketing rate C_{14}
		Warehouse utilization rate C_{15}
		Supplier return rate C_{16}
		The supplier's timely delivery rate C_{17}
		Supplier order satisfaction rate C_{18}
	Information flow B_3	Supply chain information sharing rate C_{19}
		Timeliness of information transmission C_{20}
		Accuracy of information transmission C_{21}

3. Evaluation Algorithm of Supply Chain Collaboration Degree in Manufacturing Enterprises

3.1 Fuzzy Matter and Compound Fuzzy Matter Element

In matter–element analysis, the object M and its feature C and magnitude X constitute the matter element R. Then according to the matter-element analysis method combined with the characteristics and value of objects, the functional relationship between objects can be established, as follows:

$$R = (M, C, X) \tag{1}$$

If the magnitude X in the matter-element model is ambiguous, then it is a fuzzy matter element. If the object M has n features $C_1\ C_2...C_n$ and corresponding magnitudes $X_1\ X_2...X_n$, then R is an n-dimensional fuzzy matter element, expressed as:

$$R = (N, C, X) = \begin{bmatrix} N\ C_1\ X_1 \\ C_2\ X_2 \\ \cdots \\ C_n\ X_n \end{bmatrix} \tag{2}$$

Step 1. The classical domain matrix is a matter-element matrix composed of the standard range of things and their characteristics, denoted as R.

$$R_j = (N_j, C_i, X_{ji}) = \begin{bmatrix} N_j\ C_1\ X_{j1} \\ C_2\ X_{j2} \\ \cdots \\ C_n\ X_{jn} \end{bmatrix} = \begin{bmatrix} N_j\ C_1\ (a_{j1}, b_{j1}) \\ C_2\ (a_{j2}, b_{j2}) \\ \cdots \\ C_n\ (a_{jn}, b_{jn}) \end{bmatrix} \tag{3}$$

In Formula (3), N_j represents the jth evaluation grade, C_i represents the ith evaluation index, and X_{ji}= (a_{ji}, b_{ji}) represents the range of the evaluation parameter C_i in evaluation grade N_j, which becomes the classical domain.

Step 2. The nodal domain matrix is composed of describing objects, their features and corresponding ranges of magnitude, denoted as R_p.

$$R_p = (N_p, C_i, X_{pi}) = \begin{bmatrix} N_p\ C_1\ X_{p1} \\ C_2\ X_{p2} \\ \cdots \\ C_n\ X_{pn} \end{bmatrix} = \begin{bmatrix} N_j\ C_1\ (a_{p1}, b_{p1}) \\ C_2\ (a_{p2}, b_{p2}) \\ \cdots \\ C_n\ (a_{pn}, b_{pn}) \end{bmatrix} \tag{4}$$

Among them, NP denotes the totality of the evaluation grade, C_i represents the ith evaluation index, X_{pi} = (A_{PI}, B_{PI}) represents all values of C_i, that is, section field of p.

Step 3. Determine the matter-element matrix to be tested.

$$R_d = (N_d, C_i, X_{di}) = \begin{bmatrix} L_1\ L_2 \cdots L_n \\ C_1\ x_{11}\ x_{12} \cdots x_{1n} \\ C_2\ x_{21}\ x_{22} \cdots x_{2n} \\ \cdots \\ C_m\ x_{m1}\ x_{m2} \cdots x_{mn} \end{bmatrix} \tag{5}$$

Among them, R_d represents the matter element to be evaluated, N_i is the ith thing, and C_i is the ith eigenvalue.

3.2 Determine the Weight Coefficient of Each Index

Step 1. Fuzzy matter-element with preferential membership

The corresponding fuzzy value of each individual index is subordinate to the corresponding fuzzy value that is, in turn, subordinate to the corresponding evaluation index of the standard scheme, which is called subordinate–superior–subordinate degree. Large eigenvalues of each evaluation index are suitable for scheme evaluation, whereas small and different formulas are used for calculating different membership degrees. The relativity of each synergistic index is reflected in the following form:

(1) Bigger is better

$$u_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{6}$$

(2) The smaller the better

$$u_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{7}$$

In formula (7), U_{ij} denotes optimal membership degree, while max X_{ij} and min X_{ij} denote the maximum and minimum values of each evaluation index in each scheme respectively.

Thus, R_{mn} of fuzzy matter-element matrix of membership degree can be constructed.

$$\overline{R}_{mn} = \begin{bmatrix} & N_1\ N_2 \cdots N_n \\ C_1\ u_{11}\ u_{12} \cdots u_{1n} \\ C_2\ u_{21}\ x_{22} \cdots u_{2n} \\ \cdots \\ C_m\ u_{m1}\ u_{m2} \cdots u_{mn} \end{bmatrix} \tag{8}$$

Step 2. Standard deviation fuzzy matter-element R_{0n} refers to the maximum or minimum values of the optimal membership degree of each evaluation index in the fuzzy matter-element R_{mn}. If Δ_{ij} represents the square of each difference in the standard fuzzy matter-element R_{0n} and the composite preferential membership fuzzy matter-element R_{mn}, then the difference square composite fuzzy matter-element R_Δ is established [30-32]. That is $\Delta_{ij} = (U_{0j} - U_{ij})^2$, which can be expressed as:

$$R_\Delta = \begin{bmatrix} & N_1\ N_2 \cdots N_n \\ C_1\ \Delta_{11}\ \Delta_{12} \cdots \Delta_{1n} \\ C_2\ \Delta_{21}\ \Delta_{22} \cdots \Delta_{2n} \\ \cdots \\ C_m\ \Delta_{m1}\ \Delta_{m2} \cdots \Delta_{mn} \end{bmatrix} \tag{9}$$

Step 3. Determination of entropy weight

(1) The judgment matrix of M evaluation indexes and N things $R_\Delta(\Delta_{ij})_{mn}$ is constructed.

$$R_{\Delta}(\Delta_{ij})_{mn}=\begin{bmatrix}\Delta_{11}\ \Delta_{12}\cdots\Delta_{1n}\\ \Delta_{21}\ \Delta_{22}\cdots\Delta_{2n}\\ \cdots\\ \Delta_{m1}\ \Delta_{m2}\cdots\Delta_{mn}\end{bmatrix} \tag{10}$$

(2) The judgment matrix is normalized as b_{ij}=$\frac{\Delta_{ij}-\Delta_{min}}{\Delta_{max}-\Delta_{min}}$ or b_{ij}=$\frac{\Delta_{max}-\Delta_{ij}}{\Delta_{max}-\Delta_{min}}$ to obtain $B(b_{ij})_{mn}$.

$$B(b_{ij})_{mn}=\begin{bmatrix}b_{11}\ b_{12}\cdots b_{1n}\\ b_{21}\ \Delta_{22}\cdots b_{2n}\\ \cdots\\ b_{m1}\ b_{m2}\cdots b_{mn}\end{bmatrix} \tag{11}$$

In formula (11), b_{ij}=$\frac{bij}{\sum bij}$.

(3) Determine the entropy of evaluation index

$$H_i=-\frac{1}{\ln m}(\sum_{i=1}^{m}\sum_{j=1}^{n}f_{ij}\ln f_{ij}) \tag{12}$$

This study determines the meaning of lnf_{il} as follows. When f_{ij} = 0, according to the practical significance of supply chain coordination evaluation, lnf_{il} can be understood as a large number. When multiplied with f_{ij} to 0, f_{ij} • lnf_{ij} = 0. However, f_{ij} = 1, f_{ij} • lnf_{ij} = 0, which are clearly contrary to the degree of information disorder reflected by entropy, which is not practical. Therefore, f_{ij} needs to be modified as:

$$f_{ij}=\frac{1+b_{ij}}{1+\sum_{j=1}^{n}b_{ij}} \tag{13}$$

(4) Calculation evaluation index w

$$W_{ij}=\frac{1-H_i}{\sum_{i=1}^{m}(1-H_i)} \tag{14}$$

where $\sum_{i=1}^{m}W_j=1.0\le W_j\le 1$.

Step 4. The closeness of the matter-element to be evaluated is calculated to judge the grade of the object of study. The closeness refers to the correlation between the matter-element samples and the standard ones. The large value indicates high correlation and the small value indicates low correlation between the two samples. The calculation of the closeness reflects the merits and demerits of the matter element to be evaluated.

In this study, the Euclidean distance is chosen as the basis for calculating the degree of closeness, which is expressed as:

$$R_{PH}=\begin{bmatrix} & N_1 & N_2 & \cdots & N_n\\ PH & PH_1 & PH_1 & \cdots & PH_n\end{bmatrix} \tag{15}$$

In formula (15), $PH_j=1-\sqrt{\sum_{i=1}^{m}w_i\Delta_{ij}}\quad(j=1,2,\cdots n)$.

4. Examples Analysis

In this study, Gree Electric Appliances Inc. of Zhuhai, is selected as the representative company to study the degree of synergy between upstream and downstream enterprises. Gree Electric Appliances Inc. of Zhuhai is established in 1991 as a collection of research and development, production, sales, and service in one of the international home appliances manufacturing companies. Their main home appliances are refrigerators, washing machines, and air conditioners. Its products are sold all over the world and have a high reputation. This enterprise is thus representative of the industry and is suitable to study the change trends of its upstream and downstream coordination. By investigating the production, sales, and R&D departments, and analyzing the annual report, the original order parameter data representing the development level of the company's synergy from 2011 to 2017 is obtained (Table 2).

Table 2. Enterprise evaluation index raw data from 2011 to 2017

Index	2011	2012	2013	2014	2015	2016	2017
C_1	0.3316	0.3138	0.3577	0.3523	0.2731	0.3041	0.3744
C_2	0.0761	0.0882	0.1087	0.1216	0.1525	0.1711	0.1518
C_3	0.0211	0.0293	0.0416	0.0325	0.01316	0.03705	0.3692
C_4	17.1404	18.3805	17.8434	41.99	8.8209	12.1805	25.0291
C_5	4.7509	5.7625	9.0399	20.7824	10.3173	13.8012	6.0092
C_6	1.1178	1.0794	1.075	1.1085	1.0739	1.0337	1.163
C_7	0.0589	0.2335	0.1344	0.1719	0.394	0.1171	0.1109
C_8	14.9794	19.9937	16.6154	18.7793	8.7299	4.8244	62.716
C_9	0.816	0.7899	0.7362	0.639	0.6754	0.673	0.6714
C_{10}	0.7843	0.7436	0.7347	0.8284	0.6996	0.6988	0.6891
C_{11}	0.89	0.9	0.91	0.92	0.93	0.95	0.997
C_{12}	0.98	0.99	0.992	0.995	0.995	0.999	0.999
C_{13}	0.98	0.98	0.99	0.992	0.993	0.999	0.999
C_{14}	0.96	0.97	0.95	0.99	0.99	0.996	0.996
C_{15}	0.94	0.95	0.97	0.98	0.94	0.99	0.98
C_{16}	0.025	0.026	0.01	0.02	0.015	0.015	0.01
C_{17}	0.86	0.89	0.895	0.90	0.91	0.99	0.98
C_{18}	0.87	0.85	0.90	0.91	0.925	0.93	0.95
C_{19}	0.90	0.95	0.96	0.98	0.97	0.99	0.95
C_{20}	0.85	0.87	0.89	0.90	0.89	0.90	0.98
C_{21}	0.89	0.88	0.90	0.93	0.90	0.96	0.97

4.1 Evaluation Method

Construct the compound fuzzy matter-element according to Eq. (5).

$$R_{21\times 7}=\begin{bmatrix} 0.3316 & 0.3138 & 0.3577 & 0.3523 & 0.2731 & 0.3041 & 0.3744 \\ 0.0761 & 0.0882 & 0.1087 & 0.1216 & 0.1525 & 0.1711 & 0.1518 \\ 0.0211 & 0.0293 & 0.0416 & 0.0325 & 0.0132 & 0.03705 & 0.3692 \\ 17.1404 & 18.3805 & 17.8434 & 41.990 & 8.8209 & 12.1805 & 25.0291 \\ 4.7509 & 5.7625 & 9.0399 & 20.7824 & 10.3173 & 13.8012 & 6.0092 \\ 1.1178 & 1.0794 & 1.0750 & 1.1085 & 1.0739 & 1.0337 & 1.1630 \\ 0.0589 & 0.2335 & 0.1344 & 0.1719 & 0.3940 & 0.1171 & 0.1109 \\ 14.9794 & 19.9937 & 16.6154 & 18.7793 & 8.7299 & 4.8244 & 62.7160 \\ 0.8160 & 0.7899 & 0.7362 & 0.6390 & 0.6754 & 0.6730 & 0.6714 \\ 0.7843 & 0.7436 & 0.7347 & 0.8284 & 0.6996 & 0.6988 & 0.6891 \\ 0.8900 & 0.9000 & 0.9100 & 0.9200 & 0.9300 & 0.9500 & 0.9970 \\ 0.9800 & 0.9900 & 0.9920 & 0.9950 & 0.9950 & 0.9990 & 0.9990 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \tag{16}$$

The optimal membership matrix $R_{21\times 7}$ is calculated from Eq. (8).

$$R_{21\times 7} = \begin{bmatrix} 0.5775 & 0.4018 & 0.8351 & 0.7818 & 0.0000 & 0.3060 & 1.0000 \\ 0.0000 & 0.1274 & 0.3432 & 0.4789 & 0.8042 & 1.0000 & 0.7968 \\ 0.0223 & 0.0453 & 0.0799 & 0.0543 & 0.0000 & 0.0671 & 1.0000 \\ 0.5133 & 0.5898 & 0.5567 & 2.0464 & 0.0000 & 0.2073 & 1.0000 \\ 0.0000 & 0.0631 & 0.2675 & 1.0000 & 0.3472 & 0.5645 & 0.0785 \\ 0.6504 & 0.3534 & 0.3194 & 0.5785 & 0.3109 & 0.0000 & 1.0000 \\ 0.0000 & 0.5210 & 0.2253 & 0.3372 & 1.0000 & 0.1737 & 0.1552 \\ 0.1754 & 0.2620 & 0.2037 & 0.2411 & 0.0675 & 0.0000 & 1.0000 \\ 0.0000 & 0.1475 & 0.4508 & 1.0000 & 0.7944 & 0.8079 & 0.8169 \\ 0.3166 & 0.6088 & 0.6726 & 0.0000 & 0.9246 & 0.9304 & 1.0000 \\ 0.0000 & 0.0935 & 0.1869 & 0.2804 & 0.3738 & 0.5607 & 1.0000 \\ 0.0000 & 0.5263 & 0.6316 & 0.7895 & 0.7895 & 1.0000 & 1.0000 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \quad (17)$$

Construct a difference squared fuzzy complex element matrix $R_\Delta(\Delta_{ij})_{21\times 7}$ according to the standard fuzzy matter element and the preferred membership degree matrix R_{mn}.

$$R_\Delta(\Delta_{ij})_{21\times 7} = \begin{bmatrix} 0.1785 & 0.3579 & 0.0272 & 0.0476 & 1.0000 & 0.4816 & 0.0000 \\ 1.0000 & 0.7615 & 0.4314 & 0.2715 & 0.0383 & 0.0000 & 0.0413 \\ 0.9559 & 0.9114 & 0.8466 & 0.8943 & 1.0000 & 0.8703 & 0.0000 \\ 0.2369 & 0.1683 & 0.1965 & 1.0950 & 1.0000 & 0.6284 & 0.0000 \\ 1.0000 & 0.8778 & 0.5365 & 0.0000 & 0.4261 & 0.1896 & 0.8492 \\ 0.1222 & 0.4180 & 0.4632 & 0.1777 & 0.4749 & 1.0000 & 0.0000 \\ 1.0000 & 0.2294 & 0.6002 & 0.4393 & 0.0000 & 0.6828 & 0.7137 \\ 0.6799 & 0.5446 & 0.6341 & 0.5760 & 0.8696 & 1.0000 & 0.0000 \\ 0.0000 & 0.0217 & 0.2033 & 1.0000 & 0.6310 & 0.6527 & 0.6674 \\ 0.1002 & 0.3706 & 0.4525 & 0.0000 & 0.8549 & 0.8656 & 1.0000 \\ 1.0000 & 0.8218 & 0.6611 & 0.5178 & 0.3921 & 0.1929 & 0.0000 \\ 1.0000 & 0.2244 & 0.1357 & 0.0443 & 0.0443 & 0.0000 & 0.0000 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \quad (18)$$

Using the entropy method to determine the weight

(a) Matrix $B(b_{ij})_{mn}$ can be obtained from formula (11). $b_{ij}=\frac{bij}{\sum bij}$

$$B(b_{ij})_2= \begin{bmatrix} 0.0028 & 0.0056 & 0.0004 & 0.0007 & 0.0155 & 0.0075 & 0.0000 \\ 0.0155 & 0.0118 & 0.0067 & 0.0042 & 0.0006 & 0.0000 & 0.0006 \\ 0.0149 & 0.0142 & 0.0132 & 0.0139 & 0.0155 & 0.0135 & 0.0000 \\ 0.0037 & 0.0026 & 0.0031 & 0.0170 & 0.0155 & 0.0098 & 0.0000 \\ 0.0155 & 0.0136 & 0.0083 & 0.0000 & 0.0066 & 0.0029 & 0.0132 \\ 0.0019 & 0.0065 & 0.0072 & 0.0028 & 0.0074 & 0.0155 & 0.0000 \\ 0.0155 & 0.0036 & 0.0093 & 0.0068 & 0.0000 & 0.0106 & 0.0111 \\ 0.0106 & 0.0085 & 0.0099 & 0.0090 & 0.0135 & 0.0155 & 0.0000 \\ 0.0155 & 0.0152 & 0.0124 & 0.0000 & 0.0057 & 0.0054 & 0.0052 \\ 0.0140 & 0.0098 & 0.0085 & 0.0155 & 0.0023 & 0.0021 & 0.0000 \\ 0.0155 & 0.0128 & 0.0103 & 0.0081 & 0.0061 & 0.0030 & 0.0000 \\ 0.0155 & 0.0035 & 0.0021 & 0.0007 & 0.0007 & 0.0000 & 0.0000 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \quad (19)$$

(b) F_{ij} matrix obtained from formula (13).

$$f_{ij}=\begin{bmatrix} 0.9712 & 0.9739 & 0.9689 & 0.9692 & 0.9835 & 0.9757 & 0.9685 \\ 0.9769 & 0.9733 & 0.9684 & 0.9660 & 0.9625 & 0.9619 & 0.9623 \\ 0.9352 & 0.9346 & 0.9336 & 0.9343 & 0.9358 & 0.9340 & 0.9215 \\ 0.9543 & 0.9533 & 0.9537 & 0.9670 & 0.9656 & 0.9601 & 0.9508 \\ 0.9578 & 0.9560 & 0.9510 & 0.9431 & 0.9494 & 0.9459 & 0.9556 \\ 0.9622 & 0.9666 & 0.9673 & 0.9630 & 0.9674 & 0.9753 & 0.9603 \\ 0.9608 & 0.9495 & 0.9549 & 0.9525 & 0.9461 & 0.9561 & 0.9566 \\ 0.9472 & 0.9452 & 0.9465 & 0.9457 & 0.9499 & 0.9518 & 0.9373 \\ 0.9586 & 0.9582 & 0.9556 & 0.9439 & 0.9493 & 0.9490 & 0.9488 \\ 0.9637 & 0.9597 & 0.9585 & 0.9652 & 0.9525 & 0.9524 & 0.9504 \\ 0.9619 & 0.9593 & 0.9569 & 0.9548 & 0.9530 & 0.9500 & 0.9472 \\ 0.9932 & 0.9814 & 0.9800 & 0.9786 & 0.9786 & 0.9780 & 0.9780 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \tag{20}$$

(c) Entropy H_i can be obtained from formula (12).

H_i = (0.0498, 0.0488, 0.0422, 0.0469, 0.0457, 0.0485, 0.0462, 0.0447, 0.0458, 0.0469, 0.0463, 0.0514, 0.0490, 0.0501, 0.0480, 0.0475, 0.0476, 0.0497, 0.05111, 0.0475, 0.0463)

(d) Weight W_i of Indicators Obtained from formula (14).

W_i = (0.0498, 0.0488, 0.0422, 0.0469, 0.0457, 0.0485, 0.0462, 0.0447, 0.0458, 0.0469, 0.0463, 0.0514, 0.0490, 0.0501, 0.0480, 0.0475, 0.0476, 0.0497, 0.0511, 0.0475, 0.0463)

Calculating evaluation grade.

According to (15), the European proximity degree R_{PH} can be obtained.

R_{PH} = [0.1740, 0.2730, 0.3298, 0.4299, 0.3201, 0.4117, 0.5407]

4.2 Results Analysis

First, the weights of 21 order parameters are obtained using the entropy weight method. The calculation results are as follows. The indicators for capital flow subsystem are the net asset income rate C_1, sales profit rate C_2, and current ratio C_6; the indicators for business flow subsystem are delivery time rate C_{12}, delivery accuracy rate C_{13}, core enterprise production and sales rate C_{14}, warehouse utilization rate C_{15}, and supply business order fulfillment rate C_{18}; and the indicator for information flow subsystem is the supply chain information sharing rate C_{19}. The weights of these indicators account for a relatively large average of 0.048. Therefore, Gree Electric Appliances Inc. of Zhuhai should focus on improving the aforementioned order parameters to enhance their collaboration with upstream and downstream enterprises.

Fig. 2 illustrates the data of the Euclid approach degree; R_{PH}. Fig. 1 shows that the synergistic degree has increased annually from 2011 to 2014, and the synergistic development is stable. However, the collaboration in 2015 is lower than that in 2014. Table 2 shows that the raw data (i.e., accounts receivable turnover rate, inventory turnover rate, interest guarantee multiple, warehouse utilization rate and information transmission timely rate) in 2015 decreased compared with those of 2014. This phenomenon directly led to the decrease of synergy in 2015. Among the raw data, the turnover rate of accounts receivable in 2015 decreased by 33.1691 units compared with that in 2014. This finding indicates that the working capital in 2015 was lax in accounts receivables, which affected the normal capital turnover and solvency. The inventory turnover rate in 2015 decreased by 10.465 units compared with that in 2014. This occurrence indicates a slow inventory turnover in 2015, and no balance was observed between sales and inventory. The interest coverage ratio decreased by 10.0114 units, which indicates that the enterprise solvency declined in 2015. The utilization of warehouses in 2015 is slightly lower than that in 2014. Each order parameter controls the collaboration among subsystems in the composite system, which in turn affects the overall collaboration. Therefore, Gree Electric Appliances Inc. of Zhuhai should improve the low-level order parameters to achieve enhanced collaboration.

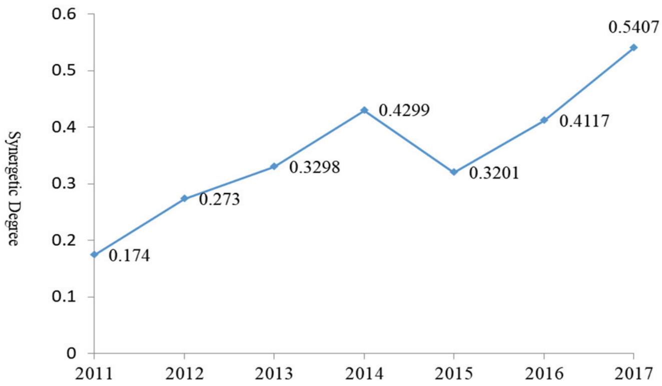

Fig. 2. Distribution of synergy degree between core enterprises and upstream and downstream enterprises from 2011 to 2017.

5. Conclusion

With the intensification of competition in the global market, the collaboration between the upstream and downstream enterprises in the supply chain to form mutual dependence, mutual cooperation, and common growth is an inevitable trend. On the basis of previous research, the present study focuses on the supply chain of manufacturing enterprises. Moreover, this work explores the collaboration and synergistic development of upstream and downstream enterprises on the basis of synergistic theory. An improved matter-element algorithm is used to calculate the order parameter weights by using the entropy weight method. The degree of enterprise cooperation is calculated by the European closeness algorithm. Thus, better accuracy can be obtained given that this algorithm avoids the disadvantages of subjectively determining the feature value and the correlation degree in the traditional matter-element algorithm. This method can also provide suggestions for companies to improve collaboration.

The collaboration model of Gree Electric Appliances Inc. of Zhuhai is established on the basis of synergistic theory and matter-element algorithm. The three subsystems and 21 order parameters of the company and the upstream and downstream enterprises are selected. Their development status is measured according to actual data from 2011 to 2017. Overall, Gree Electric Appliances Inc. of Zhuhai has a good synergistic development trend. However, the synergistic effect is still unstable and needs further improvement. In practice, the cooperation between upstream and downstream enterprises has formed a new type of coordinated development model in a continuous improvement. Enterprises are mutually integrated and promoted for the common benefit. Follow-up research can focus on how to establish the response mechanism under the influence of internal and external environmental factors of manufacturing enterprises, improve the ability of supply chain collaboration to resist sudden problems, and strengthen the construction of soft collaboration ability such as supply chain cost, comprehensive quality of labor force, industrial chain supporting, and logistics cost service system and infrastructure.

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