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Models and Methods for the Evaluation of Automobile Manufacturing Supply Chain Coordination Degree Based on Collaborative Entropy

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Abstract

Through the analysis of the coordination mechanism of the supply chain system of China's automobile manufacturing industry, the factors affecting the supply subsystem, the manufacturing subsystem, the sales subsystem, and the consumption subsystem are sorted out, the supply chain coordination index system based on the influence factor of four subsystems is established. The evaluation models of the coordination degree in the subsystem of the supply chain, the coordination degree among the subsystems, and the comprehensive coordination degree are established by using the efficiency coefficient method and the collaborative entropy method. Experimental results verify the accuracy of the evaluation model using the empirical analysis of the collaborative evaluation index data of China's automobile manufacturing industry from 2000 to 2019. The supply chain synergy of automobile manufacturing industry was low from 2001 to 2005, and it increased to a certain extent from 2006 to 2008 with a small growth rate from 0.10 to 0.15. From 2009 to 2013, the supply chain synergy of automobile manufacturing industry increased rapidly from 0.24 to 0.49, and it also increased rapidly but fluctuated from 2014 to 2019, first rising from 0.68 to 0.84 then dropping to 0.71. These results provide reference for the development of China's automobile manufacturing supply chain system and scientific decision-making basis for the formulation of relevant policies of the automobile manufacturing industry.

Keywords

Coefficient Method, Collaborative Entropy, Evaluation models, Supply Chain Coordination Degree

1. Introduction

With the upgrading of the manufacturing industry to intelligent manufacturing, supply chain coordination has become one of the core competitiveness of manufacturing enterprises, and performing intelligent manufacturing by enterprises is even more critical. When traditional manufacturing enterprises are positioning their core competitiveness, they usually only consider their own capabilities and resources and take narrow profit-generating maximization as the ultimate goal. As time goes by, science and technology are constantly updated, various collaborative problems occur frequently. Manufacturing enterprises begin to realize that their own development is not only severely limited but also face great risks, and the growth of earnings will be increasingly difficult for them.

The collaborative management of the supply chain of automobile manufacturing enterprises refers to

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the supply chain procurement, inventory, transportation, production, capital, and information link to form an entire system of collaborative management. This collaborative management also aims to ensure the orderly flow of capital, logistics, and information flow among parts and raw material suppliers, vehicle manufacturers, product sales, retailers, and consumers to maximize the overall utility of the enterprise. Many automobile manufacturers are aware of the benefits of coordination among supply chain members, and aware that supply chain collaborative management has become an effective strategy to enhance competitiveness [1]. The evaluation system of the supply chain coordination degree of automobile manufacturing can clarify each node enterprise of a supply chain coordination degree, determine the factors that threaten the supply chain coordinated operation, accurately locate the node in the supply chain system of enterprises, and improves the enterprise. Such system can not only realize the maximization of the interests of the enterprise but also guide the development of domestic automobile industry strategy for the government to provide scientific basis.

This study starts from the collaborative mechanism of automobile manufacturing industry and analyzes its impact indicators. The synergistic effect of supply chain in automobile manufacturing enterprises is constructed and calculated. The reasons for the change of synergetic scheduling among subsystems in supply chain are analyzed. A collaborative entropy method is proposed to evaluate the degree of collaboration within and among supply chain subsystems. This paper analyzes the changes of supply chain coordination in China's automobile manufacturing industry in recent 20 years. The shortcoming of this paper is that the selection of evaluation indicators for supply chain coordination of automobile manufacturing enterprises is affected by data availability.

The remainder of this paper is arranged as follows. Section 2 summarizes the research of manufacturing supply chain synergy and its evaluation. Section 3 analyzes the supply chain coordination mechanism of the automobile manufacturing industry and selects the index system that affects the supply chain coordination. Section 4 constructs the evaluation model of the degree of coordination within the subsystem of the supply chain, the degree of coordination between subsystems of the supply chain, and the supply chain system comprehensive coordination degree based on the efficiency coefficient and collaborative entropy method. In Section 5, the 2000–2019 Chinese automobile industry evaluation index data are selected for the empirical analysis. Section 6 presents a summary of the study.

2. Literature Review

Supply chain is a complex system with many functions, activities, and organizations. This complexity poses a challenge to the overall robustness and flexibility of the supply chain. To overcome these concerns, the supply chain needs to coordinate [2]. Coordination is a strategic response to the challenges posed by the interdependence of supply chain partners. Coordination is the act of managing the dependencies of entities, working together toward mutually defined goals through joint efforts. The benefits of coordination include better use of resources, lower operating costs, increased profits, improved customer satisfaction, and increased efficiency in product development [3]. Supply chain coordination can be supported by functions, such as forecasting, production management, maintenance management, distribution management, and transportation, product design, and connection between the upstream and downstream of the supply chain [4]. Most researchers have defined supply chain colla-boration as a partnership process in which no less than two independent parties work together to plan and execute supply chain operations to achieve common goals and mutual benefits. The research on supply chain management highlights the importance of coordination between enterprises. Soylu [5] reported that supply chain collaboration is a common way for enterprises throughout the supply chain to share information, establish strategic alliances to improve performance, and reduce overall costs and inventory. The ultimate goal of supply chain collaboration is to increase the company's competitive advantage. The most frequently discussed issues of sustainability and supply chain collaboration in the current literature can be divided into three broad areas, namely internal, vertical, and horizontal collaboration. Vertical collaboration is the collaboration between upstream and downstream, usually involving suppliers. Horizontal collaboration includes external collaboration with competitors and other organizations, such as "transport sharing," which allows partners to share their transportation patterns for materials and finished products to reduce costs and improve ecological efficiency [5]. In the research field of upstream and downstream collaboration, organization theory, especially stakeholder theory, is most frequently used. The theory suggests that the externalities generated when the company's environmental and social performance are weak will affect all the company's stakeholders.

In the research field of supply chain collaboration, the most commonly used methods are survey methods [6], mathematical modeling, analytical networks, and process-based models. Gimenez et al. [7] used the data collected from the fifth round of the International Manufacturing Strategy Survey project to explore the impact of internal and external environmental plans on the economic, environmental, and social performance of enterprises. Dou et al. [8] introduced a gray analysis network, process-based model to evaluate green vendor development solutions. Tian et al. [9] proposed a multi-node non-nuclear supply chain network (SCN) model. The SCN coordination evaluation model is discussed from the aspects of industrial metabolism balance, enterprise competitiveness, contract execution ability, and information interaction ability. Labiad et al. [10] proposed a model that aimed to assess the relative performance of three well known coordination contracts for a two-level supply chain under price dependent demand. Xu and Shang [11] proposed a collaborative quality evaluation method of supply chain based on structural characteristics. On the basis of the results of the quantitative regression analysis of prior samples for collaborative quality evaluation of supply chain, the quantity of collaborative quality features was analyzed, and the quantity of collaborative quality features of block collaborative supply chain was extracted. Structural feature extraction and fusion clustering methods were used for information clustering. The collaborative quality of supply chain was evaluated on the basis of the distributed fusion results. Arshinder et al. [12] proposed a model that aimed to assess the relative performance of three well known coordination contracts for a two-level supply chain under price dependent demand. Um and Kim [13] used confirmatory factor analysis to evaluate the single dimension, reliability, and validity of large-scale surveys and used hierarchical regression analysis to test hypotheses. The research results showed that supply chain collaboration can improve corporate performance and transaction cost advantages. Wang [14] used system dynamics tools to establish a self-organizing evolution model of supply chain collaboration, which revealed the evolution process and nature of supply chain collaboration and provided a basis for the development of supply chain enterprises.

The aforementioned research shows that the collaborative evaluation of the supply chain provides a useful reference for companies to reduce operating costs, increase profits, and enhance their competitiveness. On the basis of the analysis of the aforementioned research results and the supply chain coordination mechanism of the automotive manufacturing industry, the present study proposes a new evaluation model for automotive supply chain collaboration based on collaborative entropy and provides a new idea for the evaluation of automotive manufacturing supply chain collaboration.

3. Supply Chain Coordination Mechanism and State Parameter Index System of Automobile Manufacturing Enterprises

3.1 Cooperative Operation Mechanism of the Supply Chain of the Automobile Manufacturing Industry

The goal of the collaborative management of automotive manufacturing supply chain is to achieve a balanced state among component and raw material suppliers, vehicle manufacturers, product sales, retailers, and consumers while effectively avoiding the flow of funds. The conflicts caused by the asymmetry of logistics and information flow will improve the overall operation effect of the supply chain system. Raw material suppliers, component manufacturers, equipment and parts suppliers, vehicle manufacturers, dealers, automobile retailers, customer service providers, and consumers constitute a "horizontal integrated" automobile supply chain. The supply chain of the automobile industry plays a role of connection and hub. At the same time, it also coordinates the logistics, capital flow, and information flow of supply, production, and sales. Therefore, the supply chain system of the automobile manufacturing industry depends on the coordination and efficient operation of the four subsystems of supply, manufacturing, sales, and end consumer. Fig. 1 shows the collaborative operation mechanism of automobile manufacturing supply chain.

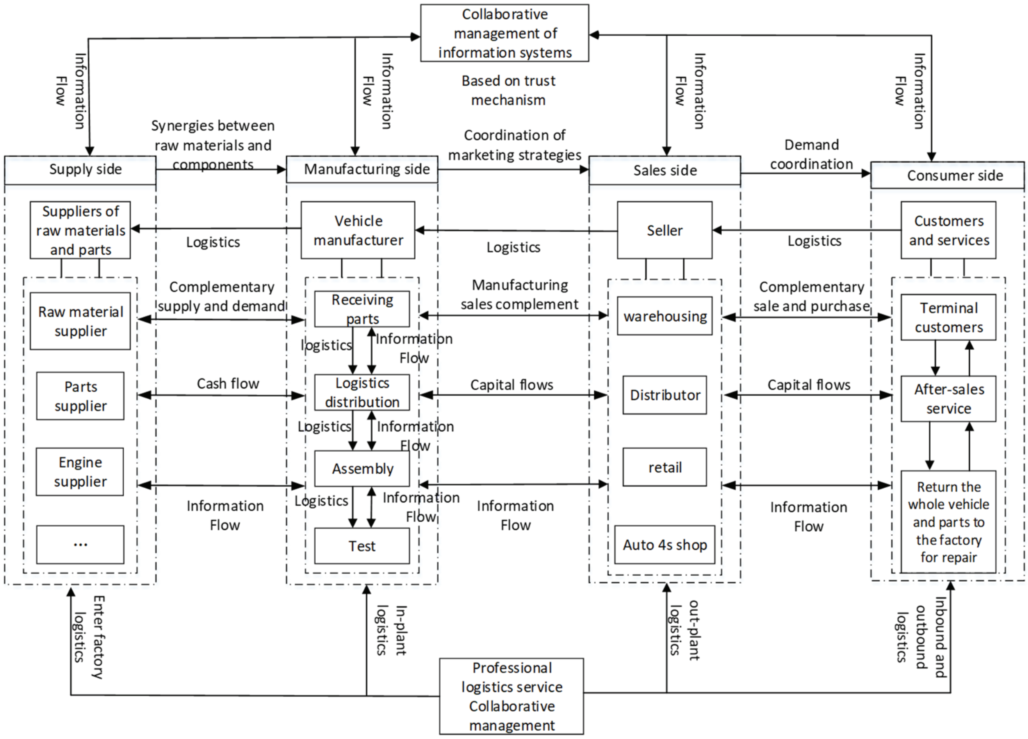

Fig. 1. Collaborative management and operation mechanism of automobile supply chain.

As shown in Fig. 1, the key to the coordination of automotive supply chain system is the internal coordination of subsystems (e.g., supply, manufacturing, sales, and consumption subsystems) and the coordination between each subsystem.

(1) From the perspective of the internal coordination of each subsystem of the supply chain, the coordination of the supply subsystem mainly depends on the collaborative effect among the raw material suppliers, parts manufacturers, and suppliers. The coordination of the manufacturing subsystem mainly depends on the coordination between the manufacturing links and the production and logistics departments [15,16]. The coordination of the sales subsystem mainly depends on the coordination among the storage, sales, and retail departments. Finally, the coordination of the consumption subsystem mainly depends on the coordination between the consumer and the customer service department and other departments.

(2) From the perspective of the coordination among subsystems of the supply chain, the coordination between supply and manufacturing subsystem, the coordination between parts supply and production, and the coordination between manufacturing and sales subsystems, they all depend on the coordination between automobile output and market demand. The cooperation between sales and consumption subsystem mainly depends on the cooperation between automobile market demand and consumer spending levels.

Therefore, the key to evaluate the comprehensive synergies of the automotive supply chain is to analyze the synergies within and among the four subsystems of the automotive supply chain.

3.2 State Parameter Index System of Automobile Manufacturing Supply Chain Collaborative System

On the basis of the cooperative operation mechanism of the automobile manufacturing supply chain, the automobile manufacturing supply chain system is divided into four links, namely the parts supply side, the automobile manufacturing side, the automobile sales side, and the automobile consumption side [17]. By analyzing characteristics of these links, the corresponding state parameters are found to provide a basis for the establishment of a collaborative evaluation index system for the automotive manufacturing supply chain.

Raw materials and parts are the first step to increase the value of auto products. Parts manufacturers use raw materials to produce auto parts and supply them to auto manufacturers to obtain benefits. In this study, the relevant state variables are found to measure the production status of component manufacturers. Therefore, seven indexes are selected for evaluation (e.g., the annual average market price of hot rolled steel, the annual average market price of natural rubber, the fixed asset investment in the auto parts industry, the number of auto parts enterprises, the annual average profit of auto parts enterprises, the annual average income of auto parts enterprises and the annual average management cost of auto parts). Particularly, the annual average market price of hot rolled steel and the annual average market price of natural rubber will influence the purchasing decision of parts enterprises and have a great influence on the production of parts [18-20]. The investment of fixed assets in the auto parts industry and the number of auto parts enterprises can reflect the production efficiency of the auto parts enterprises. Given the expansion of scale and investment, more production tools and better production technologies will be invested. Only the expansion of scale can share the cost of input. The annual income profit and the annual management expense of auto parts enterprises reflect the total production level and income of auto parts enterprises. Only the improvement of production and income level can reflect the development of supply subsystem in this link.

Automobile manufacturing subsystem is the key link in the entire supply chain system. It is the dominant force in the supply chain coordination. This study selects four state parameters to describe the state of the automobile manufacturing, namely number of auto production, total auto industry profit, total investment in fixed assets, and number of auto enterprises. Particularly, the number of auto production and auto enterprises reflects the degree of expansion of car manufacturing, auto industry profit and the total investment in fixed assets reflect the technological progress and running state of enterprises, respectively.

The sales side is an important link, which realizes the exchange of commodities and currencies, and completes the use of capital. The two state parameters of sales revenue and profit margin are adopted to reflect the status of the sales link. The sales link directly connects the market demand. It can observe the change of the market demand, connect the production link of the product, and reflect the production status.

Consumption is the fundamental purpose of all production and the driving force behind the development of the entire supply chain. People's consumption of automobiles is mainly affected by two aspects, namely the number of automobiles per 1,000 people own and the total retail sales of automobile products. With the improvement of national income and travel conditions, people will increase their demand for auto products. Therefore, the two state parameters of car ownership per 1,000 people and total retail sales of auto products are used to describe people's consumption status of automakers, which can be described under certain income conditions (e.g., people's preference for automobile products).

In sum, 16 state parameters are selected in this study to describe the state of automobile supply chain system. The specific index system is shown in Table 1.

Table 1. Automobile supply chain system state

Automotive supply chain system	State parameters of automotive supply chain system	Identification of state parameters
Supply subsystem	Average annual market price of hot rolled steel in China (yuan/ton)	U_1
	China's average annual market price of natural rubber (thousand yuan/ton)	U_2
	Fixed asset investment in China's auto parts industry (100 million yuan)	U_3
	Number of Chinese auto parts companies (PCS)	U_4
	Average annual profit of China's auto parts industry (100 million yuan)	U_5
	Average annual revenue of China's auto parts industry (100 million yuan)	U_6
	Average annual management expenses of China's auto parts industry (100 million yuan)	U_7
Manufacturing subsystem	China's automobile production (10,000 units)	U_8
	Total profit of China's automobile manufacturing industry (100 million yuan)	U_9
	Fixed asset investment in China's automobile manufacturing industry (100 million yuan)	U_{10}
	Number of Chinese automobile industry enterprises (thousands)	U_{11}
Sales subsystem	China's car sales (10,000 vehicles)	U_{12}
	Sales profit margin of Chinese auto companies (%)	U_{13}
	Sales revenue of Chinese auto companies (100 million yuan)	U_{14}
Consumption subsystem	China's car ownership per 1,000 people (units)	U_{15}
	Retail sales of automobile products in China (100 million yuan)	U_{16}

4. Evaluation Model of Supply Chain Synergy in the Automobile Manufacturing Industry

In the dissipative structure, the entropy value is used to measure the degree of chaos inside the system. The larger the entropy value is, the more chaotic the system and the higher the degree of disorder will be. By contrast, the smaller the entropy value is, the more orderly the system will be. In Haken's synergy theory, the order parameter is used to represent the degree of order of a system, and the change of the order parameter is used to describe the transformation of order and disorder in the system. A contradiction exists between order and disorder in the automotive manufacturing supply chain system. Order and disorder will transform into a certain order under certain conditions [21]. When the automotive manufacturing supply chain is highly collaborative, its internal order will continuously increase. Conversely, its internal order will continue to decrease. Thus, the synergy entropy is used to describe the synergy measure of cooperation among enterprises. The greater the synergy entropy value is, the worse the effect of the synergy among businesses will be. On the contrary, the smaller the synergy entropy value is, the better the effect of the synergy among enterprises will be.

4.1 The Artificial Image Dataset Experiments

On the basis of the collaborative structure of the automotive manufacturing supply chain system, suppose that the supply chain collaboration system of the automobile manufacturing industry is $S = \{S_1, S_2, S_3, S_4\}$, where $S_k = \{k = 1,2,3,4\}$ represents the subsystem of the collaborative system of the automotive manufacturing supply chain. $u_k^t = \{u_{k1}^t, u_{k2}^t, \dots u_{km}^t,\}$ indicates that m state parameters are present in subsystem S_k at time *t*; and $m \geq 1$. $u_{ki}^t = [L_{ki}^t, U_{ki}^t]$, where L_{ki}^t and U_{ki}^t are respectively the lower and upper limits of the critical point when the system is stable. In the actual calculation, $L_{ki}^t = \min\{u_{k1}^t, u_{k2}^t, \dots u_{km}^t,\}$, $U_{ki}^t = \max\{u_{k1}^t, u_{k2}^t, \dots u_{km}^t,\}$. On the basis of the principle of synergy, if u_{ki}^t is a positive index, the larger the value is, the higher the order of the system will be, and the smaller the value is, the lower the order of the system will be. By contrast, if is a negative index, the larger the value is, the smaller the system coordination order degree will be, and the smaller the value is, the higher the coordination order degree will be. The efficiency coefficient W_k^t of the sequence parameters of each subsystem is defined as follows.

$$W_k^t = \begin{cases} \dfrac{u_{ki}^t - L_{ki}^t}{U_{ki}^t - L_{ki}^t} & u_{ki}^t \text{ is positive index} \\ \dfrac{U_{ki}^t - u_{ki}^t}{U_{ki}^t - L_{ki}^t} & u_{ki}^t \text{ is negative index} \end{cases} \tag{1}$$

4.2 Synergy Measurement Model

4.2.1 Internal synergies of subsystems

In the subsystem $S_k = \{k = 1,2,3,4\}$, the contribution of the state parameter $u_k^t = \{u_{k1}^t, u_{k2}^t, \dots u_{km}^t,\}$ at time *t* to the synergy degree C_k^t of the subsystem can be determined by the synergy entropy of the efficiency coefficient value of each component. Suppose that the cooperative entropy of the state parameter $u_k^t = \{u_{k1}^t, u_{k2}^t, \dots u_{km}^t,\}$ efficiency coefficient of the subsystem $S_k = \{k = 1,2,3,4\}$ at time *t* is defined as:

$$H_{ki}^t = -\frac{W_k^t(u_{ki}^t)}{\sum_{i=1}^{n} W_k^t(u_{ki}^t)} \log \frac{W_k^t(u_{ki}^t)}{\sum_{i=1}^{n} W_k^t(u_{ki}^t)} \quad (2)$$

Then, the synergy degree of subsystem S_k^t can be expressed as

$$C_k^t = \sum_{i=1}^{n} H_{ki}^t \quad (3)$$

In the above formula, $C_k^t \in [0,1]$, the higher the value of C_k^t is, the greater the contribution of the state parameter u_{ki}^t at time *t* to the system S_k synergetic degree and the higher the system synergetic degree will be. Conversely, when the value of C_k^t is smaller, the contribution of the state parameter u_{ki}^t at time *t* to system S_k synergicity will be smaller, and the system synergicity will be lower.

4.2.2 Inter-subsystem synergy

In the research period $[t_0, t_n]$, at any time $t \in [t_0, t_n]$ in the automotive manufacturing supply chain system, the degree of coordination $P_{ij}^t (i, j = 1,2,3,4 | i \neq j)$ between its subsystems is defined as:

$$\begin{aligned} P_{ij}^t &= \frac{\operatorname{cov}(C_i^t, C_j^t)}{\delta_{C_i^t} \cdot \delta_{C_j^t}} \\ &= \frac{n\sum_{i,j=1}^{n} C_i^t C_j^t - \sum_{i=1}^{n} C_i^t \sum_{j=1}^{n} C_j^t}{\sqrt{n\sum_{i=1}^{n}(C_i^t)^2 - (\sum_{i=1}^{n} C_i^t)^2} \cdot \sqrt{n\sum_{j=1}^{n}(C_j^t)^2 - (\sum_{j=1}^{n} C_j^t)^2}} \end{aligned} \quad (4)$$

where $\operatorname{cov}(C_i^t, C_j^t)$ is the covariance of C_i^t and C_j^t, $\delta_{C_i^t}$ and $\delta_{C_j^t}$ are the standard deviations of C_i^t and C_j^t, and $n = t_n - t_0$ represents the research period. This study uses years as the unit, and *n* as the number of years.

4.2.3 System synergy

In the research period $[t_0, t_n]$, $t_m (t_m \in [t_0, t_n])$ is defined as the base period when the sub-system synergy is the smallest, and the corresponding degree of coordination is $C_k^{t_m}$. Then, the comprehensive synergies Z_S^t is defined as follows:

$$\begin{aligned} Z_S^t &= V \cdot (1 - D) \\ &= \sqrt[k]{\prod_{i=1}^{k} (C_k^t - C_k^{t_m})} \cdot \left[1 - \sqrt{\sum_{t=t_0}^{t_n} \frac{(C_k^t - V)^2}{(t_n - t_0)}} / V \right] \end{aligned} \quad (5)$$

where *V* represents the synergies of the automotive supply chain coordination at time *t*, *D* is the dispersion degree between the subsystems of the automotive manufacturing supply chain, $(1-D)$ represents the synergies and orderly matching degree of the automotive manufacturing supply chain, and $C_k^{t_m}$ is the value of the coordination order of the supply chain at time *t*.

5. Empirical Analysis

On the basis of the evaluation model of auto industry supply chain synergy and synergy evaluation indicators, this study establishes a summary table of the collaborative evaluation index data of the automotive manufacturing supply chain using China Statistical Yearbook, China Association of Automobile Manufacturers, and Internet public data. This table includes the supply, manufacturing, sales, and consumer sides of the Chinese automotive industry from 2000 to 2019 (Table 2).

5.1 Calculation Process of Supply Chain Synergy in Automobile Manufacturing Industry

MATLAB R2015a software is used to process and calculate the above data, as shown by the following steps.

Step 1: Preprocess the data. Use the logarithmic method to normalize the original data of various parameters of supply chain coordination in China's automobile industry, and eliminate dimension.

Step 2: Use formula (1) to calculate the efficiency coefficient of the subsystem of the automobile manufacturing supply chain by state parameters.

Step 3: Put the efficiency coefficient calculated in Step 2 into Formula (2), and calculate the internal coordination degree C_k^t of the four subsystems of the automobile manufacturing supply chain at the supply side, the manufacturing side, the sales side and the consumer side according to formula (3). The calculation result is shown in Fig. 2.

Step 4: Calculate the synergy degree between each subsystem. Conduct ADF (Augmented Dickey-Fuller Test) unit root test and Johansen's co-integration test for the synergy degree sequence of the four subsystems calculated in Step 3 to assess whether a long-term stable equilibrium relationship exists among them. Table 3 shows the ADF test results of the four time series, c_1^t, c_2^t, c_3^t, and c_4^t. As shown in Table 3, the supply chain system in the four subsystems of the original sequence is refused to the unit root hypothesis, and they are all nonstationary sequences. The respective first-order difference sequences reject the existence of units at least at the 95% confidence level, and they all show the balance. In conclusion, the four series of are first-order stationary to meet the Johansen co-integration test conditions. Table 4 shows the test results. Trace and max-eigenvalue tests are used to make the test conclusion stable. The results in Table 3 show that at least three co-integration equations are present among the four subsystem sequences and that a long-term equilibrium relationship exists between the subsystems.

Step 5: Through the test of Step 4, use formula (4) to calculate the coordination degree between the subsystems, and calculate the coordination value between the supply side and the manufacturing side of the subsystem, the coordination value between the manufacturing side and the sales side, and the collaboration degree between the sales side and the consumer side. Fig. 3 shows the synergy curve between the subsystems.

Step 6: Finally, use formula (5) to calculate the comprehensive synergy Z_S^t of the automotive supply chain system in each year, as shown in Fig. 4.

Table 2. Collaborative evaluation index data of the Chinese automotive manufacturing supply chain from 2000 to 2019

Year	State parameters of the supply subsystem							State parameters of the production subsystem				State parameters of the sale subsystem			Consumption of subsystem state parameters	
	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}	U_{15}	U_{16}
2000	3457	8.642	59.06	1480	84	1019.25	96	206.82	172	87.1	4.19	208.622	14.3	3756	12.8	1652
2001	3122	11.79968	48.05	1558	108	1359	114	234.15	204	121.06	4.3	235.854	11.8	4253	14.2	1818
2002	2659	14.32	71.73	2025	163	2125	138	325.37	373	170.27	4.56	324.314	15.5	5947	16.03	2033
2003	2976	15.6	122.63	3398	221.98	2635	155.97	444.35	556	313.03	5.06	432.934	15.5	8144	18.5	2218
2004	3245	12.105	145.39	4278	155.36	2906	109.98	507.05	575	430.02	5.91	506.118	14.1	9134	21.2	2513
2005	3768	11.98	209.97	5415	114.94	3449	124.43	570.77	526	396.21	7.22	575.739	10.7	11895	24.3	2838
2006	4193.33	21.134	240.46	6142	170.91	3838	164.06	727.97	789	415.16	7.93	718.356	5.4	15463.5	38.5	3173
2007	4376.75	20.199	253.8	7171	265.317	3731.345	201.97	888.25	1231.4	1994.6	8.83	879.152	6.5	17059.3	43.12	4348
2008	5152.21	22.734	229	8303	318.47	4843.355	236.682	934.51	1299.1	2843.5	10.03	938.05	6.1	20832	48.7	5899
2009	3888.67	16.372	277.25	10468	366.907	5692.117	280.985	1379.1	2478.05	3286.4	12.4	1364.479	11.3	25945.9	57.09	8714
2010	4431.08	26.263	430.44	11583	674.752	8425.642	371.83	1826.47	3667.9	4682.5	13.6	1806.194	13.5	36812.8	67.76	13365
2011	4883.96	33.652	554.39	8396	771.733	10963.08	478.722	1841.89	4053.18	6854.2	9.83	1850.511	10.6	47152.8	78.52	15650
2012	4214.96	24.964	598.6	9341	807.402	12398.67	584.944	1927.18	4065.28	8244.1	10.57	1930.641	10.6	50531.6	89.28	16881
2013	3895	19.752	446.8	10333	976.624	14841.84	694.444	2211.68	5107.74	9492.8	11.6	2198.408	10.9	59692.6	100.98	18553
2014	3537.08	13.521	476.8	11110	1167.624	16296.71	792.518	2372.29	5990.97	10384.5	12.41	2349.189	11.1	67818.5	112.93	33397
2015	2647.21	11.597	1159.4	12090	1298.778	17753.74	749.588	2450.33	6071.4	11859	13.43	2459.758	10.9	71069.4	125.33	36006
2016	2831.97	13.07	2108.63	12757	1527.553	20449.68	1076.391	2811.88	6677.8	12338.9	14.13	2802.818	11.1	81347.2	140.59	40723
2017	3890.25	13.818	2437.576	13333	1835.196	24153.58	1572.361	2901.54	6833.9	13476.03	14.77	2887.89	9.1	84637.1	156.42	42222
2018	4297.04	12.221	2650.377	13019	1680.849	22908.05	1375.666	2780.92	6091.7	13678.5	15.17	2808.058	6.1	83372.6	172.2	38948
2019	4077.2	12.179	2762.753	13750	1256.435	18427.3	994.19	2572.1	5086.8	13473.322	15.4	2576.9	6.3	80846.7	185.71	39389

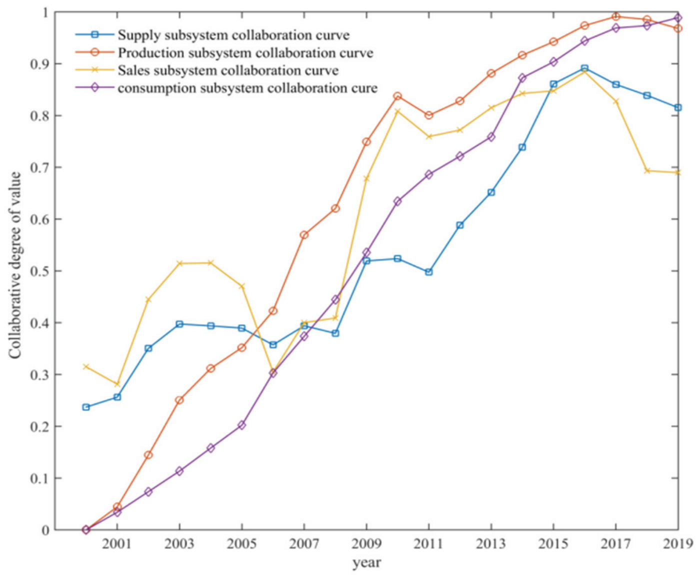

Fig. 2. The variation curve of the degree of coordination within the subsystem.

Table 3. Augmented Dickey-Fuller unit root result

Variable	Boolean decision value, *h*	Accept the null hypothesis probability, *p*	t-Statistic, *t*	0.05 Critical value	Conclusion
C_1'	0	0.9803	1.8518	-1.9602	Non-stationary series
$\Delta(C_1')$	1	0.0080	-2.7944	-1.9614	Stationary series
C_2'	0	0.9948	0.1212	-3.6736	Non-stationary series
$\Delta(C_2')$	1	0.0207	-4.1797	-3.6908	Stationary series
C_3'	0	0.7700	0.3287	-1.9602	Non-stationary series
$\Delta(C_3')$	1	0.0020	-3.3939	-1.9614	Stationary series
C_4'	0	0.9978	1.3395	-3.0299	Non-stationary series
$\Delta(C_4')$	1	0.0466	-3.07757	-3.0404	Stationary series

Table 4. Johansen co-integration test result

Null hypothesis	Eigenvalue	Trace statistic	0.05 Critical value	*p*-value	Conclusion
Trace test					There are 3 co-integrating equation(s)
None (trace test indicates no co-integrating equation(s))	0.813204	58.55047	47.85613	0.0036*	
At most 1	0.508184	28.35117	29.79707	0.0727	
At most 2 (trace test indicates 2 co-integrating equation(s))	0.432741	15.57746	15.49471	0.0486*	
At most 3 (trace test indicates 3 co-integrating equation(s))	0.258052	5.372562	3.841466	0.0204*	
Max-eigenvalue test					There are 3 co-integrating equation(s)
None (max-eigenvalue test indicates no co-integrating equation(s))	0.813204	30.1993	27.58434	0.0225*	
At most 1	0.508184	12.77371	21.13162	0.4733	
At most 2	0.432741	10.2049	14.2646	0.1988	
At most 3 (max-eigenvalue test indicates 3 co-integrating equation(s))	0.258052	5.372562	3.841466	0.0204*	

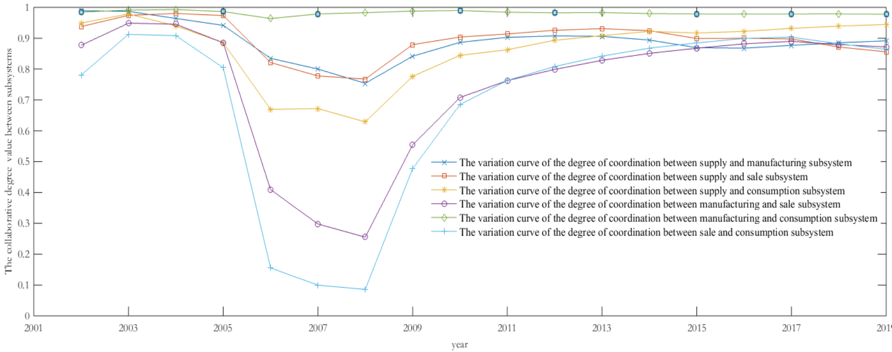

Fig. 3. The variation curve of the degree of coordination between the subsystems.

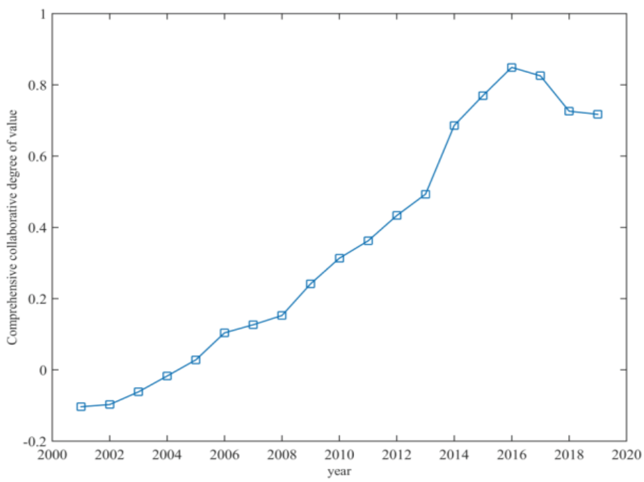

Fig. 4. China automobile manufacturing supply chain coordination degree trend chart.

5.2 Analysis of the Results of Coordination Degree

As shown in Fig. 2, the change trend of the synergy value in the supply, manufacturing, sales, and consumer sides of the subsystems of the Chinese automotive supply chain is consistent, showing an upward trend. This result indicates that the internal synergy of each subsystem is gradually improving during 2000–2019. From the perspective of the fluctuation range, the fluctuation range of the manufacturing and consumption subsystems is relatively small. This result indicates that with the increase of GDP, the gradual expansion of automobile consumption market and the gradual increase of automobile manufacturing output, the internal coordination degree of manufacturing and consumption subsystem shows a stable trend. The supply and sales subsystems fluctuate considerably. Hence, these subsystems are greatly affected by domestic and foreign political and economic factors. Drastic changes occur in the supply and sales subsystems of the internal coordination when the price of raw materials, organizational management, and enterprise investment changes.

As shown in Fig. 3, the change trends of the synergy curve between the supply and manufacturing subsystems, the manufacturing and sales subsystems, the sales and consumer subsystems are generally consistent, and they have undergone the process from being a synergy to not synergy and then to synergy again. This change truly reflects the changes in the supply chain system of China’s automobile manufacturing industry. Moreover, in the 20 years from 2000 to 2019, the synergy value between the various subsystems of the Chinese automobile manufacturing supply chain has undergone three stages: a period of rapid decline (2001–2008), a period of rapid increase (2009–2011), and a period of steady rise (2012–2019). The rapid decline in the first phase is mainly due to the fact that the Chinese automobile industry is under the original planned economic system. The government uses administrative means to manage enterprises and the market. Moreover, the supply, production, and sales of automobiles are under the same institutional constraints to achieve relative supply chain coordination. The degree is relatively high. However, due to the excessive, scattered, low-level repeated construction and repeated introduction of automobile factories, the automobile industry has become China’s pillar industry. Since China joined the World Trade Organization (WTO) in 2001, the auto industry has accelerated the pace of reforms in management systems, economic and trade policies, foreign investment policies, and market policies to transition to a market economy as soon as possible. Since then, the auto industry has been under pressure to accelerate opening up. During this period, the synergy among the various subsystems of China’s auto manufacturing supply chain has dropped sharply. Particularly, the emergence of the global financial crisis in 2008 has led to various issues in China’s auto manufacturing supply chain, the degree of collaboration between subsystems reaches the lowest value. The second phase of the rapid rise is mainly due to the approval of the “Automobile Industry Adjustment and Revitalization Plan (2009–2011)” by the State Council of China in January 2009, which proposed to focus on the development of independent brands, actively develop new energy vehicles, and encourage individuals to use energy-saving and small-emission vehicles and introduce preferential policies. During this period, in view of the reorganization, market transformation, government policy support, and other factors, the degree of synergy among the various subsystems of the Chinese automobile manufacturing supply chain has risen sharply. The third stage of steady increase mainly originated in 2012 when the state issued the “Energy-saving and New Energy Vehicle Development Plan (2012–2020).” In May 2015, the State Council of China issued “Made in China 2025,” which provides a policy guarantee for the stable development of China’s automobile industry. Starting in 2016, the State Council and the National Development and Reform Commission have successively introduced a series of macro-control measures, such as streamlining administration and delegating power, simplifying administrative licensing, opening up new energy investment areas, strengthening exit mechanisms, and strengthening mid-term and later supervision. Thus, the government has further accelerated the pace of market-oriented reforms, intending to give full play to the role of market mechanisms, promote structural adjustment, and create a fair and just market environment. During this period, the degree of synergy among the various subsystems of China’s automotive manufacturing supply chain has risen steadily. As shown in Fig. 3, during the period of steady rise, the synergy between the manufacturing and sales subsystems, between the sales and consumer subsystems declined slightly from 2017 to 2019 due to the trade war between China and the United States that began in 2018. This phenomenon led to a rapid rise in the price of China’s auto parts, which increased cars’ manufacturing costs and forced China’s auto industry to adjust its supply chain system, resulting in a slight decline in the degree of coordination among the subsystems starting in 2018.

As shown in Fig. 4, the overall synergy of China’s automotive manufacturing supply chain system is on the rise year by year. It shows that the supply chain system of China’s automobile manufacturing industry has steadily improved after its entry into the WTO and experienced the 2008 economic crisis, and also indicates the correctness of China's domestic automobile industry policies. Since 2017, the overall synergy of China’s automobile manufacturing supply chain system has decreased slightly mainly due to the trade war between China and the United States. China’s auto industry is affected by factors such as the increase in the prices of raw materials for companies upstream of the supply chain, which has led to a decline in the synergy of China's auto industry supply chain.

6. Conclusion

This study first summarizes various evaluation methods for supply chain synergy. Then, on the basis of the analysis of supply chain synergy mechanism in China's automobile manufacturing industry, a new evaluation model is constructed for the internal, inter-subsystem, and comprehensive synergy degrees using collaborative entropy method. The accuracy and the practicability of the evaluation model proposed in this study are verified based on the collaborative evaluation index data of automobile supply chain in China from 2000 to 2019. The experimental results show that the evaluation results of the supply chain synergy of China's automobile manufacturing industry are consistent with the coordinated development of the supply chain of China's automobile manufacturing industry. The findings can reflect the changes in supply chain synergy brought about by major decisions and major economic events, indicating that the evaluation model is correct and operable. However, subject to the availability of data, this study has a certain bias in the selection of evaluation index data, which is the evaluation index of data availability. In follow-up research, the essence of supply chain collaboration must be included, and specific indicators must be selected to improve the applicability of the evaluation model.

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