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A CO-EVOLUTIONARY BASED SIMULATION MODEL FOR LOGISTIC ORGANIZATION

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Abstract
This study investigates the inefficiencies in the logistics activities of rail vehicle manufacturing enterprises, arising from the absence of effective co-evolutionary mechanisms. The research introduces a novel approach using social network analysis and complex network techniques to simulate the co-evolution of logistics organizations. This model, incorporating both static structure analysis and dynamic network reorganization, offers a practical pathway for evolving logistic organization networks. The study's relevance is underscored by applying it to real-world simulations within CRRC Corporation Limited's subsidiaries, enhancing the collaborative efficiency and safety of logistic networks.

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Key Words: Logistic Organization, Evolution Pathway, Complex Network, Social Network Analysis, Railway Rolling Stock Manufacturers

1. INTRODUCTION

Railway vehicles symbolize modern urban transportation and are essential to city infrastructure and image development [1, 2]. Most railway rolling stock manufacturers currently lack a logistics-oriented mindset. This results in poorly organized logistics management with unclear value orientation, leading to disorganized design logic and dispersed logistics functions. In such an organizational structure, logistics struggle to demonstrate their potential value and become a limiting factor in production enhancement.

In reality, logistic activities of these manufacturers primarily involve the distribution and transportation of materials, products, or finished goods under data-driven operations. This includes large-scale transport, recyclable packaging, and the movement of locomotives from production to final sale [3, 4]. However, due to the scattered distribution of these activities across various subsidiaries and the absence of a central logistics department, the efficiency of logistic organizations in these enterprises is low. This results in prominent 'small group' issues and a lack of networked operation among different organizations. Therefore, constructing an effective logistic organization simulation model is a primary concern for implementing logistics management in these enterprises.

Logistic organization modelling and simulation include two main aspects: (1) Analysis of the static characteristics of the organizational structure, focusing on the network of relationships among actors at a given time, analysing influencing factors of organizational behaviour, and effectively achieving coordination and project management. (2) The dynamic evolution of the organizational network, representing the process from disorder to order, with a structure that is neither completely regular nor random, but governed by inherent self-organizing principles.

This paper aims to design a general evolutionary mechanism to guide the efficient and safe development of logistic organization networks in railway rolling stock manufacturers. Our method, combining Social Network Analysis (SNA) and Barabasi–Albert (BA) networks, is applicable to most organizational management issues in these enterprises. Based on a real-world simulation of logistic organization evolution in 12 subsidiaries of China Railway Rolling Stock Corporation (CRRC), we discuss the evolution characteristics of network organizations under

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a preferential connection mechanism, aiming to enhance the collaborative efficiency and safety of logistic networks, and establish coordinated outcomes.

2. RELATED WORKS

Logistics management is a crucial aspect of business operations, particularly in the network economy where logistics become a bottleneck in enhancing competitiveness and achieving significant growth [5, 6]. Current research mainly focuses on collaborative methods within logistic organizations. Suchanek et al. proposed a mathematical model and simulation study to optimize logistic decision-making processes, reducing costs, and increasing efficiency [7]. Lu and Zhou used complex adaptive system theory to analyse the evolution of urban logistic industrial clusters, exploring their self-organization, self-regulation, and adaptive mechanisms [8]. Liu and Li adopted the traditional concept of network service organization collaboration to address intelligent logistic service issues [9]. Pan et al. argued that supply chain and logistics organization and management would continually evolve towards collaboration, intelligence, and service orientation to meet increasingly complex customer demands [10]. Jensen and Hertz studied the impact of different roles within organizations on collaboration in humanitarian logistics organizations [11]. Huiskonen and Pirttilä researched logistic outsourcing relationships and inter-organizational collaboration issues, discussing the potential of various forms of horizontal coordination mechanisms as a source of competitive advantage for logistic service providers [12].

Organizational simulation involves combining qualitative individual behaviours, organizational phenomena, and task processes to effectively address issues caused by organizational complexity. Current research methods are relatively concentrated. System dynamics mainly simulate business processes from a macro-organizational perspective [13]. For example, Li et al. explored the evolution of supply networks through agent simulation, revealing the stability of network structures and the impact of long-term cooperation on adaptability [14]. Due to the dual attributes of 'social network' and 'business network' in the logistic organizations of railway rolling stock manufacturers, along with the diversity of enterprise types and complexity of organizational relationships, their collaborative processes involve a wide range of factors. Therefore, it's unrealistic and impractical to solve research issues solely through business process simulation or individual behaviour simulation. SNA focuses on studying the network of relationships among actors within organizations, analysing the factors influencing organizational behaviour, and effectively achieving organizational relationship collaboration and project management [15-18].

The collaboration in logistic organizations of railway rolling stock manufacturers primarily involves the coordination of logistics business processes and logistics information resources between organizations, essentially being the coordination of inter-organizational relationship networks [19]. However, logistic organization networks are not static; they undergo a dynamic and orderly evolutionary process. Their network connection structure is neither completely regular nor random but follows inherent rules [20, 21]. The current research on network evolution simulation is extensive. This paper focuses on the application of complex network technology in conjunction with the characteristics of organizational networks, integrating strategies such as "node attributes", "node addition", and "edge reconnection" with the structural features of the network [22, 23]. Many real-world networks exhibit preferential connection phenomena, where the likelihood of connecting to a node is related to that node's degree. Constructing a BA scale-free network can simulate the entry of new nodes into logistic organization networks (changing the N value) and connect them with a certain probability to nodes with a larger degree distribution, expanding the network scale [24].

Many scholars have obtained significant insights into the theories and mechanisms of organizational collaborative evolution. However, research on the organizational evolution simulation of logistic systems is still in its early stages, and there is an urgent need for more realistic evolutionary methods to guide practice. This paper, based on SNA and complex network technology, uses relevant metrics to study the collaborative characteristics of organizations. Combined with simulation tools, it models the evolution process of organizational collaboration, determining the outcomes of collaboration.

3. EVOLUTION PROCESS MODEL

3.1 Model description

Our evolutionary model is divided into two parts (Fig. 1). The first part is 'Logistics Organization Network Structure Analysis'; the second part is 'Logistics Organization Network Reorganization'. The structure analysis aims to determine the overall characteristics of the network and the status of node enterprises. Through network reorganization, the logistics organization network can evolve and reconnect based on its development process and structural features. The parameters and symbols used are summarized in Table I.

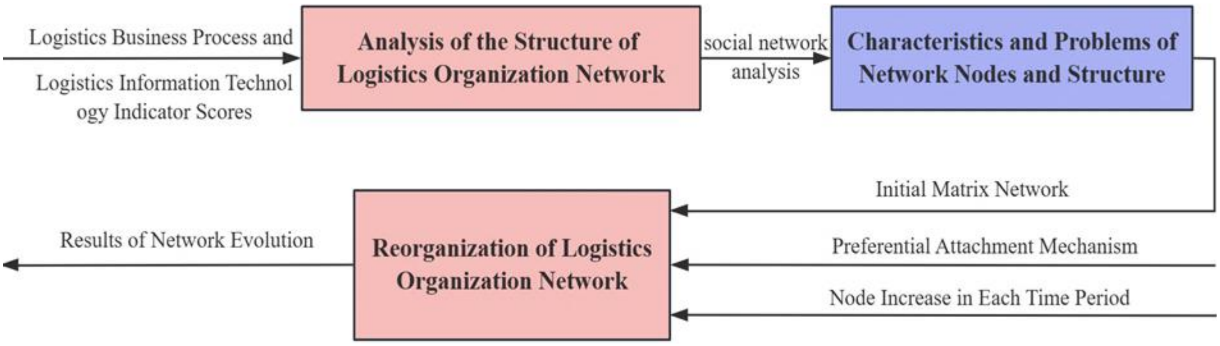

Figure 1: Evolutionary simulation model of logistics organization in railway rolling stock manufacturing enterprises.

Table I: Model-related parameters.

Parameter	Meaning	Parameter	Meaning
t	Time	e	Number of new nodes added
n_t	Number of nodes at time t	q	Number of connection edges for new nodes
m_t	Number of node connection edges at time t	p	Connection probability
G_t	Network at time t	ω_1, ω_2	Weights of the overall indicators
r_{ij}	Degree of association between logistics nodes	s_{l1}, s_{l2}	Scores of primary sub-indicators

The logistics organization network structure analysis is based on the logistic functional attribute data, using SNA to analyse the characteristics and connections of nodes within the railway rolling stock enterprise's logistics organization network, thereby depicting the network's overall structure. Additionally, the output of this structure analysis, in the form of initial network matrix data and evolutionary rules, serves as the input for the logistics organization network reorganization. This reorganization evolves the network through preferential connection and node growth mechanisms and involves the following steps:

1. Construction of a logistic functional attribute indicator system

Considering the requirements for logistics service informatization and digitalization in railway rolling stock manufacturing enterprises, this paper proposes a logistic functional attribute evaluation indicator system that spans logistic business processes, information, and resources (Table II). These criteria, researched and confirmed by experts from the CRRC Group, are applied using a six-level Likert scale, assigning sub-indicator scores from 0 to 5 to minimize evaluation errors due to subjective expert judgments.

2. Weighted evaluation and scoring of the logistics organization network

To analyse relationships within the logistic organization, this study employs the Delphi method to weight and score the degree of collaboration among nodes of case enterprise organizations. The calculation formula for each node j's weighted evaluation score for node i's logistic functional attributes in the entire logistics organization network is as follows:

$$r_{ij} = \sum_{l=1}^{a} \omega_1 s_{l1} + \sum_{l=1}^{a} \omega_2 s_{l2} \quad i, j = 0, \dots n \tag{1}$$

3. Social Network Analysis (SNA)

We organize r_{ij} to create the initial network of the logistics organization in railway rolling stock manufacturing enterprises. Then, we analyse network measures such as node centrality to understand the current structure of the network.

Table II: Logistic functional attribute indicators information.

Overall indicator	**Primary sub-indicator**	**Secondary sub-indicator**	**Details**
Logistics Business Process	Procurement Logistics	Material Purchasing	Purchasing of raw materials and components, and order management.
		Material Transportation and Reception	Transporting raw materials and parts from suppliers to the manufacturing plant and quality inspection.
		Warehousing Management	Safe and effective storage of raw materials and components for production.
	Production Processing Logistics	Material Handling	Moving materials and components within the factory to support the production process.
		Inventory Management	Managing inventory of semi-finished and finished products.
	Shipping Logistics	Finished Product Assembly	Assembling various parts to manufacture the final railway vehicles.
		Packaging and Handling	Ensuring finished products are safely packaged and handled for transportation.
		Transportation Management	Safely and effectively transporting finished products to customers or final destinations.
Logistics Information and Resources	Logistics Resources	Logistics Infrastructure	Facilities for storing raw materials, parts, semi-finished, and finished products.
		Transportation and Loading/Unloading Equipment	Trucks, flatbeds, or equipment for moving goods within a yard, used for transporting raw materials, parts, and finished products.
	Logistics Information	Information Technology	Technology software for tracking and managing logistics business processes.

4. Network preferential connection expansion

New nodes are added to the logistic organization network of the railway rolling stock manufacturing enterprise, and are connected preferentially. At $t = 0$, the model initializes as an initial graph $G_0(n_0, m_0)$ with n_0 nodes and m_0 edges. We add e nodes to G_0 along with q edges originating from the new nodes, forming the new network G_{t+1}. As new logistic nodes join, the network scale gradually expands. The connections between logistic organizations have certain preferences but do not fully adhere to the degree-preferential connection principle; newly entering logistic organizations tend to connect with existing ones having higher logistic functional attributes. Therefore, based on the expansion of the BA network, the connection rules between a newly entering logistic organization and the existing ones in G_t are set as follows:

(1) The number of edges q originating from a new node is less than or equal to n_0.

(2) The probability of each node in G_t connecting with a new node is:

$$p = \frac{r_{ij} + 1}{\sum_j (r_{ij} + 1)} \tag{2}$$

3.2 Simulation of a real organization

We applied the model described in the previous chapter to the actual logistics organization network of a railway rolling stock manufacturing enterprise. This network comprises 12 subsidiaries of CRRC, including 9 primary subsidiaries and 3 secondary subsidiaries. Each organization has its own business division, and there are logistic business contacts and cooperation between the logistics organizations (logistics departments within the organizations). The current structure of the logistics organization is shown in Fig. 2.

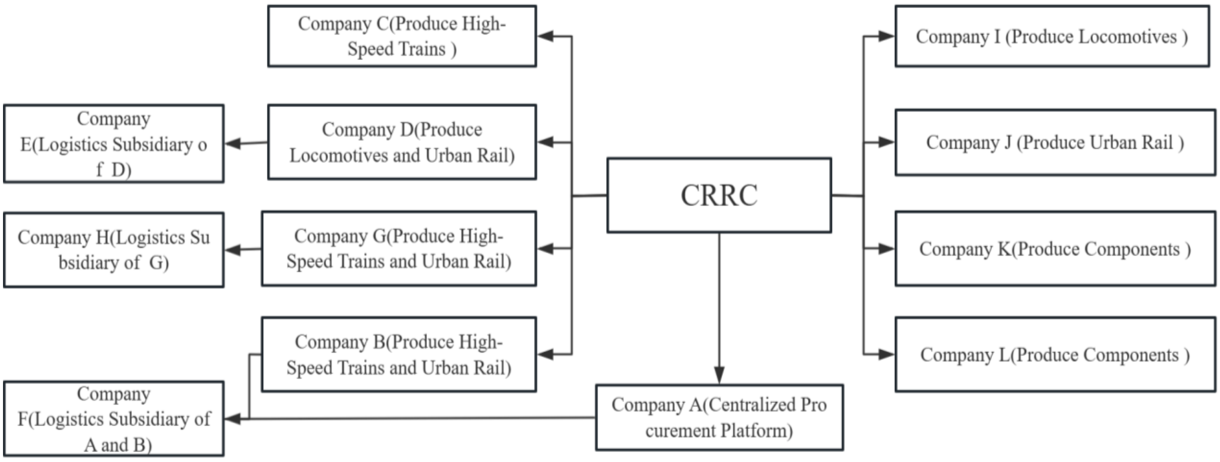

Figure 2: Logistics organization structure of CRRC Group.

In this study, experts from CRRC confirmed the weights of logistic business process attributes (ω_1) and logistic information resources (ω_2) as 0.65 and 0.35, respectively. We conducted a survey on the logistics activities of each organization over the past year. The respondents were from various subsidiaries with diverse job backgrounds such as production of parts, whole vehicle manufacturing, centralized procurement, information technology, etc., and held various managerial positions like general manager, vice president, sales manager, logistics manager, etc. After collation, we obtained the initial network data of the logistics organization (Table III).

Table III: Initial network data of the logistics organization.

Comp.	**G**	**C**	**B**	**D**	**I**	**J**	**K**	**L**	**A**	**F**	**H**	**E**
G	13	3	3.7	1.05	1	1	3.9	3.3	3.3	3.65	8.75	0.1
C	3.1	13	3.1	2.15	1.45	1.45	2.1	4.35	3.75	6.5	0.8	0.2
B	1.05	1.05	13	1.05	0.7	0.7	3.35	3.35	2.8	9.45	3	0
D	0.7	0.7	0.7	13	0.7	0.7	0.7	0.7	3.05	1.3	1.3	5.05
I	2.6	2.6	2.6	2.6	13	3.2	2.6	2.6	3.9	3.55	2.6	3.5
J	0	0	0	0	1.4	13	0	0	2	0	0	0
K	6.35	4.7	6.35	6.35	1.15	1.15	13	1.15	2.45	3.9	2.9	1.4
L	6.7	6.7	6.7	4.7	2.6	2.6	2.6	13	3.15	9.4	6.45	0.1
A	2.8	2.8	2.8	2.8	2.8	2.8	4.2	4.2	13	4.2	3.25	2.75
F	4.5	4.8	6.1	4.8	3.9	3.9	4.8	4.8	5.6	13	4.5	4.5
H	10.65	0.7	0.7	0.7	0.7	0.7	3.25	0.7	1.9	3.4	13	0.7
E	3.05	3.05	3.05	6	4.7	3.05	3.05	3.05	3.05	2.6	2.6	13

In our model, logistic functional attributes are the criteria for preferential node connection. The logistics organizations of CRRC Group need to further strengthen their logistics business processes and logistic information resources to achieve collaborative development of the logistic organization. In terms of the model's evolution, it starts with an initial 12 nodes, and with each period, e new logistics organization nodes are added, continuing the increase until there are 1000 nodes.

4. SIMULATING RESULT

4.1 Logistics organization network structure analysis

This paper utilizes the NetDraw software in UCINET 6.0 to analyse the network structure characteristics of CRRC Group's logistics organization (Table IV). In the logistics organization network, 'in-degree' indicates the number of connections entering a node company, and 'out-degree' indicates the number of connections emanating from the node company. These respectively represent the degree to which the organization is influenced by other organizations and its ability to influence other organizations.

Table IV: Centrality of nodes in the logistics organization of CRRC.

Degree centrality				**Closeness centrality**				**Betweenness centrality**	
Out-degree	**Rank**	**In-degree**	**Rank**	**Out-degree**	**Rank**	**In-degree**	**Rank**	**Centrality**	**Rank**
52.20	F	47.95	F	13.0	E	20.0	J	4.61	A
51.70	L	41.50	G	12.0	G	12.0	B	4.61	I
37.85	K	36.15	H	12.0	D	11.0	I	0.11	G
37.25	E	35.80	B	12.0	C	11.0	A	0.11	D
35.40	A	34.95	A	12.0	K	11.0	G	0.11	C
32.75	G	32.20	D	12.0	L	11.0	D	0.11	K
32.35	I	30.55	K	12.0	B	11.0	C	0.11	L
28.95	C	30.10	C	12.0	F	11.0	K	0.11	F
26.50	B	28.20	L	12.0	H	11.0	L	0.11	H
24.10	H	21.25	J	11.0	I	11.0	F	0	J
15.60	D	21.10	I	11.0	A	11.0	H	0	B
3.40	J	18.30	E	11.0	J	11.0	E	0	E

From the perspective of degree centrality, Company F ranks first in both out-degree and in-degree, indicating its strong attractiveness and radiative power in the logistics activities of this railway rolling stock manufacturing company, making it a core logistics company. Company A, as the group's logistics platform, does not play a central role in logistics activities and lacks sufficient contact with other enterprises. Additionally, Companies D and J, with lower rankings in both in-degree and out-degree, are on the periphery of the organization.

Regarding closeness centrality, Company E has a high external closeness centrality, indicating tight logistic connections with other companies and a strong influence. In terms of betweenness centrality, Company A holds a pivotal position in the logistics activities of the railway rolling stock manufacturing enterprise, with a relatively high status. Although Company I has a high betweenness centrality, its degree centrality and closeness centrality are lower, indicating that it mainly plays a connecting role in logistics activities but with weaker influence. Companies J, B, and E, with a betweenness centrality of zero, indicate that they rely on other companies for logistic interactions in related activities.

4.2 Logistics organization network reorganization

Based on the current network structure's issues and characteristics, we imported the initial network data into Python for simulation. This involved analysing the degree distribution, average path length, and clustering coefficient indicators to understand the dynamic reorganization process of the logistics organization in railway rolling stock manufacturing enterprises.

1. Degree distribution

$P(k)$ represents the probability that a randomly selected node has exactly k degrees. It is typically used to describe the degree distribution of nodes in a network and measure the connection intensity between logistic organizations. Simulation test results show that the degree distribution of CRRC Group's logistics organization conforms to a power-law distribution (Fig. 3). This implies that most logistic organizations have fewer channels of edge communication, with only a few organizations having more channels.

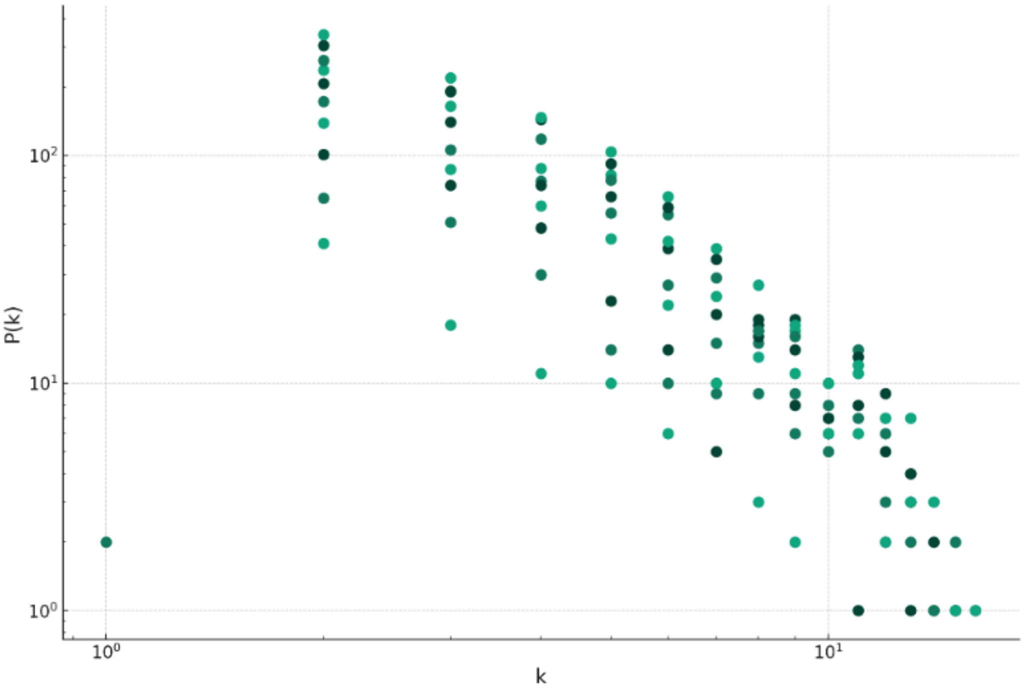

Figure 3: Degree distribution of the logistics organization.

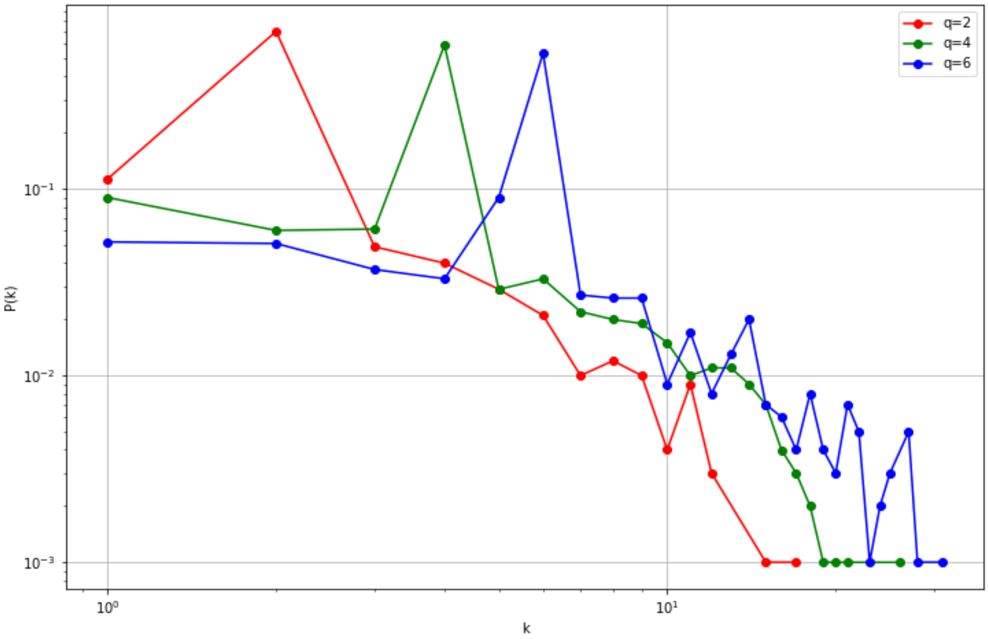

Figure 4: Degree distribution of the logistics organization under different connection methods.

The results in Fig. 4 demonstrate that the degree distribution of the logistics organization conforms to a power-law distribution, regardless of the number of connection edges for newly added nodes. This is attributed to the fact that logistics organizations with a higher degree have a higher level of logistic capabilities, including logistic business and information resources. Establishing connections with these high-degree nodes offers a greater likelihood of accessing extensive logistics resources, thereby enabling more logistics organizations to easily establish connections through these high-degree nodes.

2. Average path length

The average path length, defined as the average of distances between any two nodes in the network, reflects network connectivity and efficiency, represented by the formula:

$$L = \frac{2}{\frac{1}{2}n(n-1)} \sum_{i \geq j} d_{ij} \tag{3}$$

The simulation results in Fig. 5 show that despite the increase in the number of nodes, the average path length between logistics organizations gradually stabilizes. This indicates that most logistics organizations in the network can be connected through relatively fewer steps, suggesting an increasing trend towards "collaboration" between nodes. This occurs because, with fewer nodes initially, the cost of connecting logistics organizations is high, resulting in a longer average path. As central nodes emerge, many logistics organizations establish connections through these central nodes, slowing the growth of the average path length. Due to the network's growth and the "preferential connection" mechanism, these central nodes gradually evolve into high-degree nodes, increasing the likelihood of accessing logistics resources by connecting with them.

3. Clustering coefficient

The clustering coefficient measures the degree to which nodes in a network tend to cluster together, indicating the presence of small groups or communities. Assuming a node i in the logistic organization has k_i neighbors, without self-connections and duplicate connections, there can be a maximum of $\frac{k_i(k_i-1)}{2}$ edges between these k_i nodes. If the actual number of edges existing between these k_i nodes is E, then the clustering coefficient C of the logistics organization is calculated as:

$$C = \frac{\sum_i \left(\frac{2E_i}{k_i(k_i - 1)} \right)}{N} \tag{4}$$

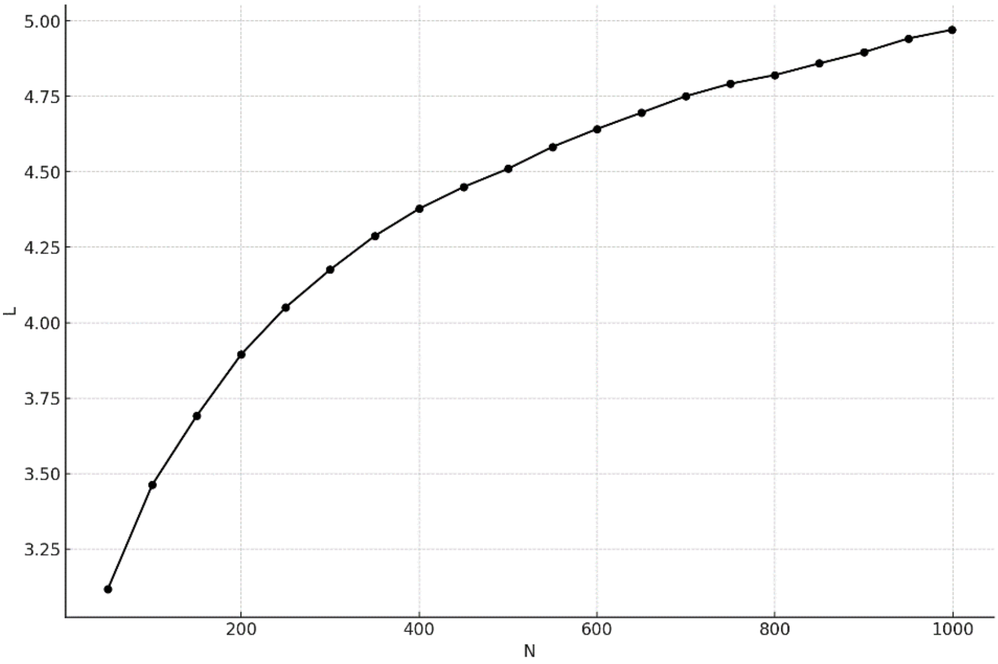

Figure 5: Average path length of the logistics organization.

Fig. 6 shows that as new logistics organizations join, the clustering coefficient gradually increases, indicating a more pronounced clustering characteristic. However, after a certain stage, the clustering coefficient of logistics organizations begins to decrease, weakening the network's clustering degree and leading to a looser structure. This suggests that over time, only a few logistics organizations have the cohesion to form groups. The phenomenon of small groups within logistics organizations gradually diminishes, and the overall organizational network becomes more mature and efficient.

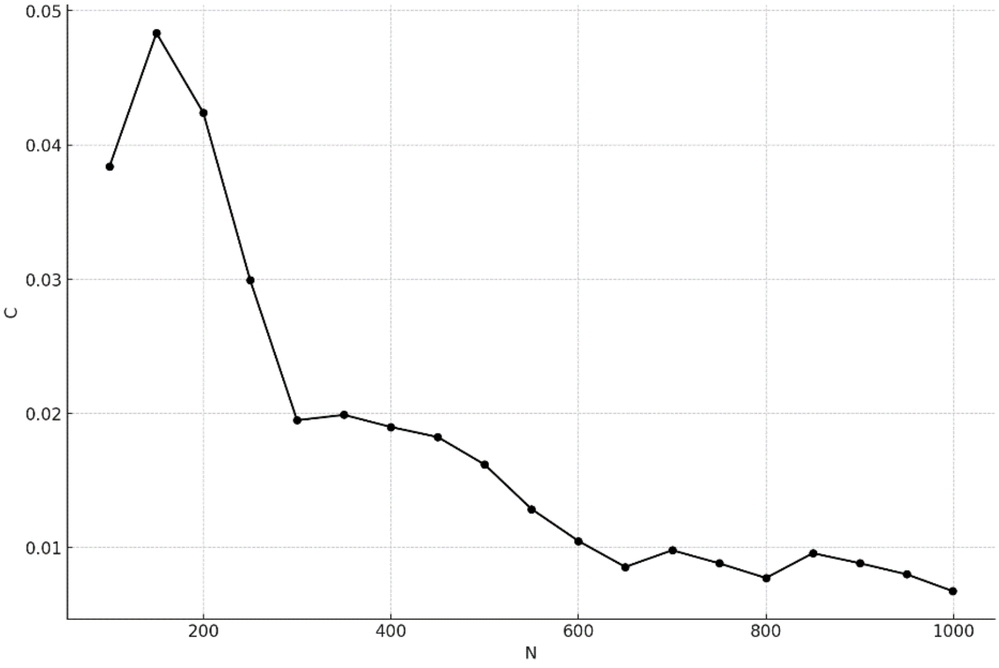

Figure 6: Clustering coefficient of the logistics organization.

4.3 Management insight

In summary, the logistics organization of railway rolling stock manufacturing enterprises undergoes a transition from initial turbulence to eventual stability. Currently, Company A, despite being a primary subsidiary responsible for logistics consolidation in CRRC Group, does not play a pivotal coordinating role. Companies F, H, and E, as secondary subsidiaries specializing in logistics, face limitations from higher-level organizations, lacking horizontal mediation and communication. This inefficiency and resource wastage hinder the marketization of the logistics industry. The network initially shows disarray, with few connections and low clustering among logistics organizations. As the structure reorganizes, common interests foster value judgments, increasing connections through a few central nodes. As the number of organizations increases, the network gradually stabilizes and becomes more efficient, collaboratively offering integrated logistics services to the market.

5. CONCLUSION

In practice, many logistics management issues can be resolved or mitigated through enhanced collaboration between enterprises. For instance, the focus on small group interests at the expense of the logistics network's broader benefits often stems from insufficient collaboration among logistics organization members. This paper aims to describe an effective method to set the evolutionary path for logistics organizations in manufacturing enterprises, ensuring improved efficiency of logistics services. The study's simulation of CRRC Group's real railway vehicle manufacturing logistics organization network in China demonstrates the model's applicability for collaborative management during enterprise development. This approach helps build a more stable and rational logistics organization structure and offers valuable insights for strategic planning in enterprise logistics. Moreover, the paper provides actionable methods for guiding the evolution of logistics organization networks in manufacturing enterprises. Future research could extend to larger-scale, multi-level logistics organization networks and validate the general applicability of logistics organization evolutionary mechanisms across different types of enterprises.

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