

Research on the Evolution of Supply Chain based on Complex Adaptive System Theory

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Abstract. The core idea and basic views of the complex adaptive system theory are expounded, and the compatibility between complex adaptive system theory and supply chain is demonstrated. With the independent enterprises participating in the operation of supply chain system as the adaptive agents, a hierarchical system model of department-enterprise-multi-agent is constructed under the theoretical framework of complex adaptive system. The whole evolution process and main characteristics of each stage of supply chain's evolution and development are revealed. The key technology system of supply chain optimization in the future is studied by using complex adaptive system theory from simulative perspective and entity optimization aspect. This paper proposes a thinking pattern to study the evolution process of supply chain by using complex adaptive system theory.

Keywords: Supply Chain; Complex Adaptive System; Hierarchical Modeling; Evolutionary Development; Self-adaption; Intelligent Agent.

1. Introduction

In the current complicated and changeable dynamic market environment, the competition of enterprises has changed from competition between individual enterprises to competition among alliances and supply chains [1]. In a rapidly changing market environment, users' needs are also correspondently unstable. In order to immediately meet the instant and diversified needs of users, the supply chain must be able to respond quickly to the fluctuating marketing environment and consequently optimize the overall supply chain operation. This is the common goal of each partner in the supply chain. The supply chain is not a simple system composed of a single linear combination of individuals on the chain, but a complex network system formed by a series of nonlinear effects [2], which is closely connected with environment and continuously evolved along with changes in the environment. At the same time, any change in the environment will have a significant impact on the overall transformation and implementation of the supply chain, leading to an increase in the uncertainty of the supply chain management. Therefore, how to select and construct the most suitable supply chain structure, optimize the performance of the supply chain, and optimize the overall structure has become a critical problem that enterprises need to solve imminently. Therefore, it is urgent to study the evolution of the supply chain, and to provide support for the supply chain optimization in China.

Since the supply chain is a complex network system [3], with complex and dynamic characteristics, coupled with the uncertainty of the market environment and the developing process of its dynamic changes, the supply chain problem must be studied as a sophisticated issue [4]. Starting from the complex adaptive system theory and based on complexity and dynamic adaptability of supply chain, this paper tries to construct a model from the perspectives of the adaptability and overall efficiency of the supply chain, and proposes a theory of applying the complex adaptive system theory to study the evolutionary development process of the supply chain. [5].

2. Supply Chain from the Perspective of the Complex Adaptive System Theory

2.1 The Central Concept and Idea of the Complex Adaptive System Theory

Complex adaptive system (CAS) theory is a system science that emerged at the end of the 20th century. In 1994, John Holland of the United States proposed “a system composed of interacting bodies described by rules.” The most basic concept of CAS theory refers to an active individual with adaptive ability, called as “the subject” for short [6]. Under the general stimulus-response model, the subject can interact with the environment, communicate with other subjects in the environment, and continuously learn in the process of communication, hence change the structure and behavior mode according to such an experience. CAS theory terms the function of repeated interaction between the subject and the environment in the system as “Adaptation”; the development or evolution of the system as a whole includes the generation, differentiation, aggregation, development of new subjects, and the hierarchical and complex nature of the system, which are all gradually derived from the basis of “adaptation”; and the changes in the system as a whole can also find the roots in the individuals’ behavioral laws. This view is the core idea of CAS theory: adaptation generates complexity [7]. CAS theory provides creative viewpoint for the cognition, understanding, controlling, and management of complex systems.

2.2 Compatibility Analysis of Supply Chain and CAS Theory

The complexity of the supply chain and market competition [8] requires that the supply chain among enterprises must be equipped with excellent adaptability, so it is appropriate to evaluate and analyze the supply chain based on CAS theory. CAS consists of a large number of adaptive subjects [9]. There are complex nonlinear interactions among subjects, and between subjects and environments, which lead to the phenomenon of “Emergence in large numbers” of the system, that is, the evolution of microscopic individuals makes the macro system display a new state and a new structure. The core of CAS theory is that individuals in the system are proactive and initiative. The adaptability of the subject is reflected in the exchange of information and resources with other subjects and the environment, and the adjustment and transformation of behavior patterns to achieve their own goals and adapt to the demand of environmental changes, which has become the basis for the evolution of enterprises’ supply chain.

The interpretation of system complexity and adaptability by complex adaptive system theory and its evolutionary thoughts are of great significance for studying the evolution of supply chain. However, to study the supply chain from the perspective of CAS, we must first prove that the supply chain is compatible with CAS. CAS has seven basic characteristics [10]. These basic characteristics are sufficient and necessary conditions for CAS [11], and the supply chain clearly matches the characteristics mentioned above from the system level to the individual level. The seven basic characteristics and their compatibility with the supply chain are shown in Table 1.

It should be pointed out that from a physical point of view: the smallest unit of the supply chain is the department that accesses each enterprise in the supply chain system. However, since most departments do not have self-adaptive optimization function and do not meet the basic requirements of the CAS theory, it is not appropriate to regard a single department as a subject. From an economic perspective, the smallest unit of the supply chain is an independent company involved in system operation. Enterprises have independent decision-making and profitability in the system, and can also adapt to the external environment [12].

Tab. 1 Compatibility Interpretation of SC and CAS Theory

Features	Comments	The Compatibility Interpretations of Supply Chain
Aggregation	The aggregation and interaction of simple subjects in CAS will emerge a great many complex large-scale behaviors.	All kinds of enterprise entities form aggregates, and complex interactions are generated at the planning and dispatching operation levels to achieve coordinated operation of the system.
Nonlinearity	The subject does not follow a simple linear relationship when interacting with the environment and adapting itself to the changes.	Various supply chains and their coupled networks have complex characteristics that cannot be expressed in linear models.
Flow	There are different forms of resource flows such as energy and information between the subjects in the CAS.	The supply chain is a multi-level network of logistics-information-value coupling. There are logistics, information flow and value flow between each level and each subject, thus realizing the allocation of resources and information.
Diversity	The subjects and complexity in the CAS system make the evolution of the system tend to be complicated.	The various types of entities at the micro level, as well as the diversified systems at the macro level, are inherently of multiplicity and diverse in all types of supply chains, which reflects the difference in the evolution of the supply chain.
Identification	Subjects of the same kind in CAS have similarities and boundaries, thus enabling classification and hierarchy.	The complementary and coordinated operation of resources in the supply chain is based on the classification, identification and hierarchical division of different subjects.
Internal model	CAS theory uses an internal model to represent a subject's certain function and mechanism.	All kinds of subjects in the supply chain have significant input-output characteristics in self-running and interactive coordination, so it is feasible to construct internal models for the subjects and the system.
Building block	The various subjects, levels and even the system itself in the CAS are composed of a variety of relatively simple building blocks.	The various types of subjects in the supply chain are composed of different energy information units; different subjects are interconnected to form different levels in the network; and thus constitute the supply chain itself.

2.3 Evolution of the Supply Chain under the CAS Framework

According to CAS theory, the supply chain is gradually transformed through the evolution of multiple stages on the basis of the original material system. The characteristics and behaviors of the system and the subjects are different at each stage. According to this evolutionary idea, combined with the existing research results of the supply chain, the conceptual framework of the evolution process of the supply chain under the CAS framework is proposed. The framework divides the evolution process of the supply chain into four stages, determines each stage some systematic characteristics and structure, and summarizes the overall evolution form and trend of the supply chain. The characteristic connotation of each stage supply chain is shown in Figure 1.

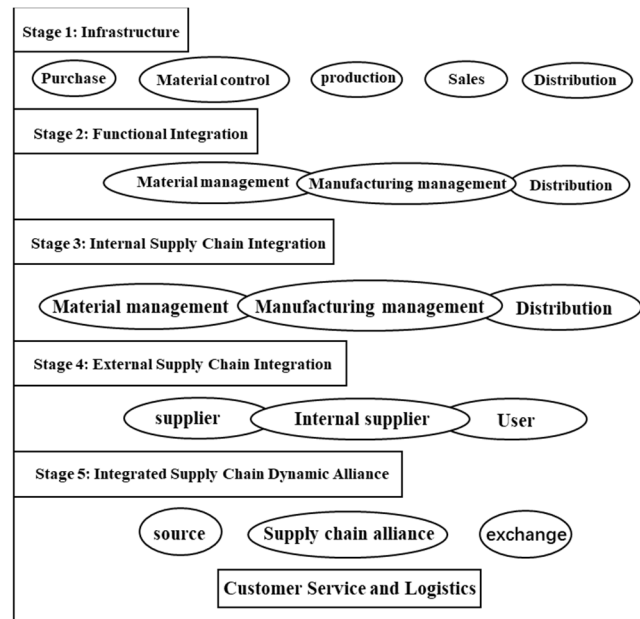


Fig. 1 Sketch Map of the Evolution Process of Supply Chain Based on CAS

Figure 1 manifests that in the first stage of the budding supply chain system, the planning, operation and optimization of the purchase, production and sales for various products are relatively independent, and the enterprises are in a state of single-handedness, but there are certain coupling relationships, such as the joint operation among some related companies. This stage is a relatively stable and long-lasting stage in the evolution of the supply chain system. The barriers between enterprises help the subjects maintain a balanced situation for a long time. Until some of the subjects in the system find that their self-adaptability is better than the planning or operation strategy of the existing model, the system stability will be broken, and the system evolution will then enter the next stage.

The evolving supply chain is the stage between the budding supply chain system and the mature supply chain. In this stage, the existing system stability is broken. Each company will strengthen cooperation with other enterprises in order to facilitate its own existence and continuity, so as to adjust its own decisions according to the actions of other enterprises. According to CAS theory, the system at this stage has two key features:

(1) Chaos, that is, existing system rules are constantly being broken, and enterprises begin to repeatedly try new operating rules [13]. The system enterprises corresponding to the supply chain begin to jump out of the existing competition cooperation framework and tries to explore new market interaction models.

(2) Emergence, new enterprises that adapt to chaos come into existence. These enterprises have various types, more complex structures, and more abundant modes of operation [14]. This is mainly manifested in the vertical integration and horizontal integration of enterprises. The essence of this phase is the deconstruction and reorganization of the current supply chain structure, which means the integration and optimization of resources. As resource allocation becomes more rational, the system will evolve into the embryonic stage of the supply chain.

In the embryonic stage of the supply chain, the type differences of enterprises in the supply chain are no longer obvious, but they form regional multi-functional enterprises with comprehensiveness, complexity, openness and adaptability. Regional multi-functional enterprises can achieve global optimization of the entire supply chain system through the integration of their own supply and demand balance and the coordinated operation with other regional multi-functional enterprises. As the system operation cycle increases, the supply chain will further evolve, eventually achieving the greatest economic and environmental benefits, and can maintain a relatively strong adaptive target state under the conditions of external environmental changes.

3. Modeling of Supply Chain Subjective Relationship in the CAS Framework

3.1 Single Subject Modeling based on the Characteristics of Logistics Information

The first step is to build a feature model for a single department in the enterprise. Enterprises in the supply chain are made up of multiple departments through multiple forms of information connection. Therefore, the department's feature model is the basis of the enterprise model and the supply chain CAS macro model. The departments in various types of enterprises can be roughly divided into three categories, namely, the procurement department, the production department, and the sales department. A coupling matrix can be used to describe the relationship between the input and output of a department, denoted as A.

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} = \begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_m \end{bmatrix} \quad (1)$$

Where: a_{ij} is the coupling factor, which represents the proportional relationship between the input of the i -th material or product input I_i and the j -th material or product output O_j . By studying the characteristics of material transmission and transformation in different departments and different situations, the values of the coupling coefficients in the coupling matrix corresponding to each department can be determined.

The second step is to build a logistics-information feature model for the entire enterprise.

Based on the modeling of individual departments, building models for the entire enterprise requires solving problems from two aspects:

- (1) To characterize the logistics features of the enterprise as a whole;
- (2) To realize the presentation of subjects' self-adaptive mechanism [15].

The critical step to solve the first problem, namely the characterization of the overall logistics features of the enterprise, is to connect and expand the characteristics of the departments. To this end, it is necessary to clarify the key links of material flow in the subject: ① Logistics input, that is, the enterprise accepts raw materials from the upstream link of the supply chain. ② Optimization: To analyze the needs of downstream enterprises, optimize the logistics in the enterprise through scheduling algorithms and resource allocation. The resources that the enterprise optimizes can be transmitted from the superior system or the enterprise's own resources. ③ Storage: On the one hand, analyzes the characteristic requirements of inventory in the enterprise, on the other hand, analyzes the storage requirements of various products outside the enterprise, and thus regulates various warehouses to ensure the balance of enterprise materials. ④ Output: The processed materials are exported to the downstream enterprises in the supply chain. ⑤ Feedback: To analyze product quality and material dissipation for the company's operational process, and optimize the related algorithms and decisions of the enterprise. In general, the logistics characteristics of a single enterprise in the supply chain, that is, the logistics input and output model can be expressed by the formula (2).

$$\text{Output}, n = \text{Input}, n \prod_{i=1}^m A_i \quad (2)$$

In the formula: Output, n and Input, n are respectively the output and input matrices of the n -th enterprise; A_i represents the coupling matrix of the i -th department in the n -th enterprise; m is the number of departments in the enterprise.

In addition, the coupling matrix in equations (1) and (2) can be further extended as follows: the process of materials in the flow process can be divided into two categories:

- (1) Distribution.

(2) Transmission or processing transformation.

With regard to material distribution, it refers to the distribution of various materials to different departments in a certain proportion, which can be described by the distribution rate.

The transmission of materials or processing transformation refers to the materials are converted in a variety of means to be involved in the production after the input to the department with a certain conversion efficiency. Therefore, the coupling matrix A can be further expanded to:

$$A = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nm} \end{bmatrix} \begin{bmatrix} \eta_{11} & \eta_{12} & \cdots & \eta_{1m} \\ \eta_{21} & \eta_{22} & \cdots & \eta_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \eta_{n1} & \eta_{n2} & \cdots & \eta_{nm} \end{bmatrix} \quad (3)$$

In the formula: d_{ij} is the distribution factor, indicating the proportion of the i -th material distributed to the j -th product; η_{ij} is the efficiency factor, indicating the proportion of the i -th material processed into the j -th product. According to different transformation links, matrix A can be further expanded into multiple allocations and efficiency matrices.

For the second problem, the representation of the enterprise's self-adaptive mechanism refers to the adjustment of the company's own behavior according to the information of the supply chain system. Specifically speaking, the enterprise's self-adaptation mechanism is also composed of two parts: ① Each enterprise optimizes its own operation strategy according to the information on supply chain system under the framework of the existing supply chain system. ② Adjust the characteristics of the enterprise through planning of the latest resources and detection to the updated rules so as to improve the adaptability of the enterprise in the supply chain system.

For the enterprise's self-adaptive approach, it is necessary to start from the information transmission of the enterprise and clarify the information-logistics coupling mechanism of the enterprise. The information transmission of enterprises includes the following links. a) Information input: The enterprise receives information from both the upstream and downstream links of the supply chain system. b) Decision-making and controlling: To make decisions about the operation strategies of the enterprise's internal departments based on the collected information, thereby controlling the logistics. c) Information output: To transmit real-time logistics information to the enterprises in the downstream of the supply chain system; and transmit the material demand information of the enterprise to the upstream enterprises. The logistics-information coupling mechanism of a single enterprise is demonstrated in Figure 2.

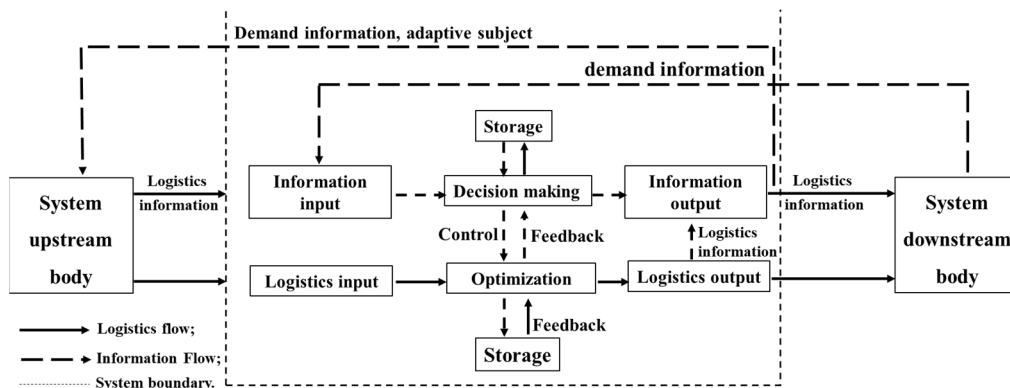


Fig. 2 Diagram of supply chain single adaptive subject logistics-information coupling mechanism

3.2 Multi-Enterprise Relationship of the Logistics-Information-Economic Coupling

According to the CAS theory, the key to the transition from the micro-level subject model to the macro-level system model is to clarify the way in which the subjects are connected and to establish an interaction model system of the subjects [16]. In the supply chain environment, logistics and

information flow will be the key form of enterprises to connect each other. Due to the free and open market attributes of supply chain, the value stream generated by inter-enterprise transactions is another key link among the enterprises. The coupling relationship between logistics, information flow and value stream are shown in Figure 3.

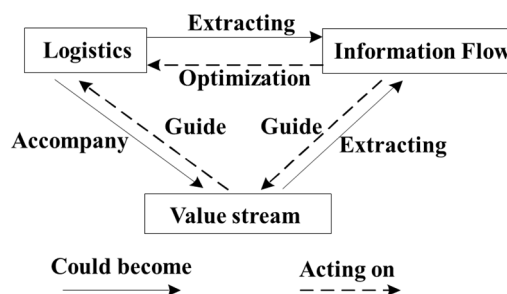


Fig. 3 Coupling Relation of the Flow of Logistics-Information-Value in SC

In general, logistics reflects the physical characteristics of the supply chain in CAS, the information flow reflects the informational characteristics of the system, and the value stream reflects the economic characteristics of the system. The specific form of interaction among different types of enterprises in the supply chain can theoretically be attributed to the logistics-information-economy coupling relationship [17]. By portraying various forms of interaction from the perspectives of logistics, information flow, and value stream, it is clearer and more definite to determine the interactions among enterprises in the supply chain, as shown in Figure 4.

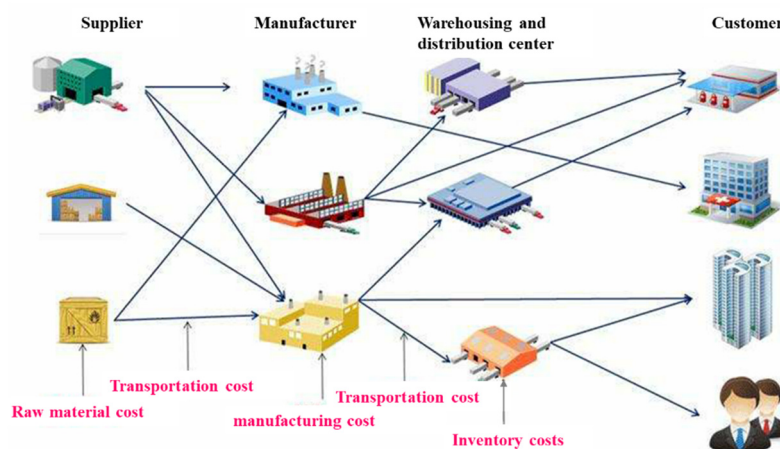


Fig. 4 Model Architecture Diagram of Supply Chain in CAS

In fact, the essence of the “inter-subject interaction” in the supply chain is the various business models in the system. Therefore, the nature of the model architecture of Supply Chain in CAS displayed by Figure 4 is the market framework of the supply chain system. In the market framework, diversified subjects adjust their own programming and operation modes according to the logistics-information characteristic model established in Section 4.1, and improve their adaptive ability in the system through evolving individual self-adaptation so as to achieve the operational goals or criteria.

4. The Practicality of CAS Theory with the Development of New Technology and Evolution of the Supply Chain

There are two main levels of objectives in studying the supply chain under the CAS theory framework:

(1) To explore the evolution mechanism, development path and final shape of the supply chain through analogue simulation based on the evolution theory of complex adaptive systems.

(2) To guide the optimization of the supply chain in practice through employing supply chain's rules of the evolution and development obtained by the application. The realization of the above objectives requires the support of analogue simulation and physical construction as the basis of the serial key technologies.

4.1 The Key Technology of Analogue Simulation

Analogue Simulation is the nuclear method to study CAS, and it is also an important method to explore the evolution of supply chain. At the theoretical research level, a relatively systematic Agent modeling technology system has been established, which can basically realize the decision-making and learning behaviors of enterprises in the system [18]; while at the theoretical application level, there have been preliminary applications of the current CAS simulation technology in the financial market and enterprise management. The supply chain system is more comprehensive and complex compared with other systems. Therefore, the simulation research of the supply chain CAS still demands support from more advanced models and platform technologies.

In the future, the key technology of analogue simulation in the field of the supply chain in CAS will develop from the following four aspects:

(1) Research on logistics-information-economic modeling theory and technology of the supply chain in CAS revolving around the logistics information structure and market mechanism of the supply chain;

(2) To break through the multiple scenario simulation technology supported by large-scale networks for large-scale supply chains;

(3) To expand and deepen the existing multi-agent simulation platform, and develop a simulation platform of supply chain that supports transmission of logistics and information, and economic behaviors;

(4) To establish a status assessment system for the supply chain system from the perspectives of energy efficiency optimization, information security, and mechanism reasonableness. Through the above technologies, the reliable simulation of the evolution process of the supply chain could be realized, and the rules of enterprise behaviors and the characteristics of system structure in each stage of supply chain's evolution would be revealed.

4.2 Key Technologies of Physical Construction

It is difficult but crucial to study the supply chain under the CAS theory framework by applying the rules of analogue simulation to the physical supply chain. Concerning the theory of CAS and the evolution of the supply chain, the essence of the key technology on supply chain optimization under the CAS theory framework is the fusion technology of the logistics information based on big data platform.

The big data technology platform has been a popular research at home and abroad in recent years, and has also been considered as a systematic solution for the information engineering project of supply chain. In the future, big data are still the key technology platform for realizing the integration of the logistics information of supply chain. It is necessary to establish a big data theory and technology system on supply chain with a series of theoretical researches.

5. Conclusion

This paper proposes a theoretical method to study the evolution process of supply chain taking the advantage of the complex adaptive systems: It proves the compatibility of supply chain and complex adaptive system theory; It defines the independent economic individuals in supply chain as the subjects in the complex adaptive systems, and puts forward the supply chain research under the framework of complex adaptive system from three different levels of department, enterprise and enterprise interaction based on the logistic, informational and economic characteristics in the supply

chain; The framework model of supply chain's evolution process under the framework of complex adaptive system is also proposed and the main characteristics of the supply chain in each stage are analyzed; The key technologies for the future evolution and development of the supply chain by applying further research on CAS are discussed from the perspectives of the analogue simulation and physical construction.

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