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Modeling and simulation of supply network evolution based on complex adaptive system and fitness landscape ☆

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Abstract

A supply network (SN) is a complex adaptive system, and its structure and collaboration mechanism evolves over time. However, most literature views SN as a static system and the study on the evolution of SNs is very limited. Based on complex adaptive system and fitness landscape theory, this paper first proposes an evolution model of SNs in order to understand the general principle of SN evolution. Then the paper conducts a multi-agent simulation on the evolution model, and discloses that the SN emerges and evolves from firms' dynamic interaction under the dynamic environment. Dominated by the environment and firms' internal mechanism, the evolution is highly sensitive to the initial condition, and it is path-dependent and difficult to predict precisely. Although the dynamics of environments is different, a SN enjoys the stable structure in different environments. Higher level of structure stability and fitness of the SN are achieved when the firms in the SN adopt the long-term collaboration strategy rather than the short-term strategy. Finally, a China case is explored which validates the self-organization evolution of SNs.

Keywords: Operations management; Supply networks; Self-organization; System modeling; Simulation; Case study

1. Introduction

A supply network (SN) is referred to as a complex network of organizations that synchronizes a series of inter-related business processes, such as procurement, manufacturing and distribution, to create values to final customers in the form of one or more families of related products or services (Christopher, 1992; Min & Zhou, 2002). In spite of growing interest in the management of supply networks (Choi, Dooley, & Rungtusanatham,

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2001; Lamming, Johnsen, Zheng, & Harland, 2000; Stuart, Deckert, McCutcheon, & Kunst, 1998), researchers are still in an early stage of understanding how a SN behaves and evolves. Some studies investigated the factors that influence the SN evolution in different environments. For example, Hur, Hartley, and Hahn (2004) identified six factors that have influence on the structure of SNs in different industries. Choi and Hong (2002) found that the SN of Honda was controlled centrally by the final assembler, while the SN of DaimlerChrysler was decentralized. Choi et al. (2001) and Chung, Yam, and Chan (2004) proposed that a SN emerged and evolved in a way of its own. The emergence of cooperation networks was largely an endogenous process driven by the complex and dynamic interplay between institutions, products, technologies, markets and innovative actors (Bruce, 2000). What are the salient factors and the general principles that shape a SN? No one can answer this question with any degree of certainty (Harland, Zheng, Lamming, & Johnsen, 2002). This is due to the lack of our understanding of evolutionary aspects of SNs (Surana, Kumara, Greaves, & Raghavan, 2005).

This study will investigate the general principles involved in the evolution of SNs. It proposes a SN evolution model based on CAS (complex adaptive system) (Holland, 1995) and fitness landscape theory to model the dynamic behavior of the SN evolution with the dynamic interaction among the firms and the environment. This approach underscores the importance of the model in which different entities in the SN operate subject to their own local strategies, constraints and objectives. With the simulation of the evolution model based on multi-agent, the dynamic behavior of the firms and the SN can be analyzed from a variety of organizational perspectives. It finds that the evolution of SNs is a self-organization, and identifies the salient factors that control the evolution. Also, a case study which explores the evolution of a SN in China for more than 30 years validates the findings. Finally, some managerial insights are proposed in the paper.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature. Section 3 presents the system model and simulation of SN evolution based on CAS and fitness landscape theory. The principles and some salient factors that influence the SN evolution are discussed. In Section 4, a China case study is presented to validate the findings in Section 3. In Section 5, we present some propositions and managerial implications about the evolution of SN. Finally, concluding remarks and future research directions are pointed out in Section 6.

2. Literature survey

A useful paradigm for supply chain management, taking into consideration of the dynamic interaction of the firms in the supply chain, is to view it as a supply network (Surana et al., 2005). Most of the researches in the past decades viewed the SN as a static system. Analytical models, simulation methods and empirical approaches have been employed to enhance the knowledge of SNs and optimize the system decision (Pathak, Dilts, & Biswas, 2007a). Based on analytical and simulation methods, most of researches focused on the "design" and "optimization" of SNs. They tended to assume that a SN is an integrated and static organization (Gunasekaran & Ngai, 2005; Min & Zhou, 2002; Whang, 1995). Empirical studies were employed to understand the strategic issues, managerial perceptions, and measurements of key operational issues of SNs (Choi & Hong, 2002).

Although the structures and collaboration mechanisms of a SN are static in a short term, they evolve in the long run. The optimal network structure and collaboration mechanism for a SN which takes researchers' many efforts based on the assumption of static structure may become invalid as the SN evolves. To better facilitate the management of SNs, we need to understand more about the dynamic behaviors of the firms and SNs. For example, how can different firms form a SN structure? How does the SN evolve over time? To answer these issues, we need to understand the evolution dynamics of the formation, adaptation and evolution of SNs.

There exists a body of literature that deals with the supply chain as a dynamic system. These approaches are often based on various simulation methods to examine the dynamic behavior of SNs. They can generate results about large-scale systemic behavior in ways that are analytically intractable, and find how various improvement efforts affect the dynamical behavior. Forrester (1961) was the first one who examined system dynamics within a supply chain by the simulation method. Illuminating results have been generated from this line of approach (Berry, Naim, & Towill, 1995; Larsen, Morecroft, & Thomsen, 1999; Marquez & Blanchar, 2004; Swaminathan, Smith, & Sadeh 1998; Towill, 1996; Towill, Evans, & Cheema, 1997; Wikner, Towill, & Naim, 1991). Besides system dynamics, other simulation methods such as discrete-event simulation, artificial intelligence etc. has been employed to model the dynamical behavior (Alfaro & Sepulveda, 2006; Holmstrom & Hameri, 1999) and possible improvements of SNs (Holweg & Bicheno, 2002). However, most of these studies were still based on the assumption that the SN structure was deterministic and stable. They could not give insight for the understanding of the evolution of SN structure and coordination mechanism. Only a few studies took consideration of the dynamic structure of SNs, but they proposed different conclusions. For example, Akkermans (2001); Schieritz and GroBler (2003) used system dynamics and multi-agent to study the emergence and stability of SNs, while their conclusions were quite different.

Since the seminal contribution on supply chains as a CAS by Choi et al. (2001), there emerges some literature on the evolution of SN in the supply chain management discipline. Pathak, Day, Nair, Sawaya, & Kristal, 2007b provided a good review of these literatures on CAS and proposed some critical issues and challenges in the study of SNs based on CAS. Surana et al. (2005) argued that supply chains should be treated as a CAS and proposed how various methods used in the study of CAS can be exploited to characterize and model SNs. Like any CAS, some combination of control theoretic, agent-based, and discrete-event modeling approaches might be applied to study the evolution of SNs (Choi et al., 2001). Pathak and David (2002), Pathak, David, and Gautam (2003), Pathak et al. (2007a) developed a multi-paradigm dynamic system simulator based on CAS and showed that certain environmental and firm-level factors might impact the evolution of SN structures. As to the empirical methods, only a few studies viewed the SNs as CAS and proposed some arguments for the understanding of the structure and operations of SNs (Carbonara, Giannoccaro, & Pontrandolfo, 2002; Choi & Hong, 2002). With the limited literature on SNs as CAS, no one could give definite answers to how SNs behave and evolve.

In the dynamic environment, SNs do not always keep in constant, but evolve over time. The changes of the environment, the firms, and the inter-relationships within a SN, coupled with the adaptive capability of firms' responding to such changes, make the complexity of the SN evolution. Due to the evolving nature of SNs, the challenge is to develop an effective analysis tool to model the behaviors of firms and the entire network to unveil of the evolution complexity of SNs. The complexity of SNs evolution rules out the use of a single approach. A combination of approaches is necessary to adequately explore difficult issues such as nonlinearities, cyclical feedback mechanisms, emergence, and path dependencies (Pathak et al., 2007b). Based on Choi et al.'s propositions (2001) that internal mechanisms, the environment, and co-evolution are the three key foci for SN research, this paper proposes a dynamic evolution model of SNs based on CAS and fitness landscape theory and simulates the model using multi-agent technology (Pathak & David, 2002; Pathak et al., 2003). The simulation results disclose the general principles and salient factors that dominate the formation, adaptation and evolution of SNs. Also, a case study validates these findings.

3. Modeling and simulation of SNs evolution

3.1. Modeling SNs evolution

Camazine et al. (2001) defined self-organization as: "A process in which the pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern."

As argued in the evolutionary theory, self-organization can be understood on the basis of the same variation and natural selection processes, compared with other environmentally driven processes of evolution. Firms collaborate with others to fulfill the demand generated by the market where they populate. A SN emerges and evolves in a bottom-up way from the ongoing patterns of collaborations among firms. The collaboration relationship is like a weighted bi-directional graph, where the firms are the nodes and the relationships are the edges (see Fig. 1) in graph theory. The weight of an edge represents the collaboration preference between two firms. With the interaction of firms, those firms survive if they adapt to the environment, and the network structure emerges and evolves if it facilitates the collaboration.

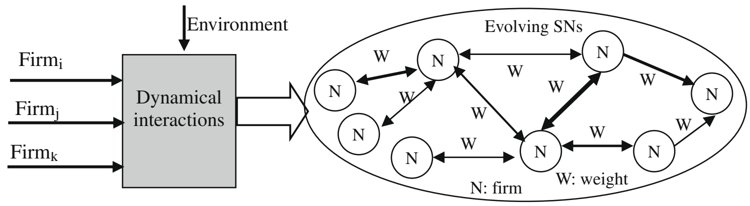

Fig. 1. The SN evolution model.

To model the self-organizing evolution of SNs, this paper not only takes account of the influence of the environment on firms' behaviors and the evolution of SNs, but also the influence of firms' internal mechanisms (e.g., strategies, capability, product, etc.) on firms' behavior and the evolution of SNs. This model can better map the dynamic behavior of an SN and the firms from the evolutionary aspects than the models of Pathak and David (2002), Pathak et al. (2003).

According to Melody's (1994) contributions, a firm can be modeled as an eight-tuple:

$$\text{Firm} = < E, S, OC, RC, OS, BP, P, F > \tag{1}$$

where they stand for the environment (E), Strategy (S), Organization Culture (OC), Resource Constraints (RC), Organizational Structure (OS), Business Processes (BP), Products (P), and Fitness (F) for a firm, respectively.

The environment places expectations on firms. Firms need to balance between environmental expectations placed on them with the resources and capability available in them (Luhmann, 1995; McCarthy, 2004). Firms co-evolve with the environment via the concept of 'fitness landscapes' (Kauffman, 1993; Kauffman and MacReady, 1995). The environment factors are classified into two groups: (1) The *Macro Environment*, which specifies the economy, politics, culture, laws, regulations, and market, etc., are exogenous to all firms (2) The *Micro Operation Ecology*, which specifies the demand, the supply, the price, the lead-time and the competitors for each individual firm. The expectations that the environment places on firms are evaluated by the environment fitness landscape F_c ($0 < F_c \leqslant 1$). A higher F_c indicates that firms are more difficult to fit to the environment. In summary, the environment is modeled as:

$$E = < Macro\ Enironment,\ Micro\ Operation\ Ecology,\quad F_c | F_c \in (0,1) > \tag{2}$$

$$Macro\ Enironment = < Economy,\ Politics,\ Culture,\ Laws,\ Regulations,\ Market,\quad F_c > \tag{3}$$

$$Micro\ Operation\ Ecology = < Demand,\ Supply,\ LeadTime,\ Price,\ Competitors > \tag{4}$$

To survive, a firm has to fit to the environment. "*This is a process of matching the environmental fit and the internal fit* (Hamel & Prahalad, 1994; Miller, 1992)". In this process, firms need to identify and realize appropriate strategies, organization structure, culture, resources, business process, and products, which are the aspects of firm's internal mechanism. A firm's fitness is denoted as $fitness_i(t)$, representing the capability of firm i to survive in one or more populations, and imitate and/or innovate combinations of capabilities, which will satisfy firm's objectives and market needs, and be desirable for competing firms at time t (McCarthy, 2004). $fitness_i(t)$ is represented as a real number in $[0, 1]$. The higher the value is, the higher the firm's ability to adapt to the environment.

$fitness_i(t)$ is usually measured by customer satisfaction and is evidenced in profit or loss. It is influenced by many factors from the environment and the internal mechanism. First, if a firm can fulfill the demand, it makes profit and its fitness increases. Therefore, it has more resource to improve its products, capabilities, etc., which further gives it more opportunity to win in the competition. Second, the firm's fitness decays over time, too. If a firm cannot get any order in a demand cycle, its fitness decreases. Third, the environment has influence on the decay speed of fitness. A fast changing world has a higher F_c, which results the greater decay speed of firm's fitness. Fourth, the decay speed of firms' fitness is influenced by social culture. If the firms in a market prefer the short-term relationship (e.g. firms in USA), the decay speed is greater than that of the firms preferring the long-term collaboration relationship (e.g., firms in Japan, China). In summary, the fitness evolution function of a firm is:

$$fitness_i(t+1) = fitness_i(t) + \Delta f[\cos t_i(t), reward_i(t)] - \Delta\delta_i(t) \quad (5)$$

$\Delta f[cost_i(t), reward_i(t)]$ is fitness variation caused by the firm's fulfillment of the demand at time t. $cost_i(t)$ is the cost to fulfill the demand, and $reward_i(t)$ is the return at time t. If a firm cannot fulfill the demand, $reward_i(t)$ is negative. $\Delta\delta_i(t)$ is the decay of firm's fitness, which is related to F_c and the social culture preference.

The internal elements of firms evolve, too. In this model, we take account of the evolution of firm's capacity and manufacturing cost. If the firm fulfills an order, it makes profit and invests in manufacturing capacity, which results its manufacturing cost be reduced.

$$MC_i(t+1) = MC_i(t) + \Delta MC_i(t) \quad (6)$$

$$CS_i(t+1) = CS_i(t) - \Delta CS_i(t) \quad (7)$$

where $\Delta MC_i(t)$ is the change of manufacturing capacity and $\Delta CS_i(t)$ is the change of manufacturing cost at time t. When a firm fulfills an order, firm's capability and cost is improved. Namely, both $\Delta MC_i(t)$ and $\Delta CS_i(t)$ are positive; otherwise, they are negative. On the other hand, if a firm cannot get any order in a demand cycle, its capacity decreases and its cost increases.

The process of interaction among firms, and between firms and the environment involves natural selection. If $fitness_i(t)$ is higher than F_c, firm i survives. Otherwise, firm i is eliminated from the environment. There is a positive feedback between firm's fitness and the probability to win in the competition. A firm with the higher fitness has more opportunities to win the competition. Therefore, the goal for a firm is to improve its fitness by responding to the challenges and opportunities posed by the environment.

In summary, the evolution model of a SN is represented as:

$$SN(t) = f(environment, \mathrm{firm}_i, \ldots, \mathrm{firm}_m) = G(t) =< V_t(G), E_t(G), P_t(G) > \quad (8)$$

where there are m firms residing in the *environment*. With the dynamic interaction of firms, there emerges the evolving SN which is like a bi-directional graph $G(t)$. $V_t(G)$, $E_t(G)$ and $P_t(G)$ are the collections of nodes, edges and collaboration preference of firms at time t, respectively.

3.2. Simulations of SNs evolution and analysis

The evolution model is simulated based on multi-agent technology. In the simulation, each firm is designed as an autonomous agent, which has strategies, rules, resource constraints, business process, products and fitness. The culture factors are integrated in the firm's strategy and operation rules. Firms who manufacture the same product can be a buyer as well as a seller. The market is set as a Bertrand model, where firms compete in two stages. (1) In the first stage, the market is a monopoly, where the firm with the highest fitness wins the global demand from the market, and manufactures the product subjected to its capacity; (2) the second stage is a competition market, where the winner in the first stage subcontracts the remaining demand to the rest firms. The winner selects its subcontractor according to its collaboration strategy (price priority, short-term, or long-term collaboration strategy) and the rest firms compete in price for the remaining demand. Firms' operation rules are: (1) competing for demand without considering of capacity constraint; (2) when the demand is greater than its capacity, it subcontracts the remaining demand to the others. At the beginning of the simulation, each firm's internal elements (fitness, capacity, cost) and the elements of the environment (demand) are initiated randomly. At the end of each demand cycle, each firm's fitness, capacity and cost are updated. And then, the environment evaluates each firm's the fitness and eliminates the firms whose fitness are less than F_c.

There are eight firms (numbered from 0 to 7) involving in the experiments. The demand in each demand cycle is generated randomly in accord with a Uniform distribution $U[D_{\min}, D_{\max}]$, where $D_{\min}$ and $D_{\max}$ are the lower and upper limits of the market demand, respectively. The initial capacities of each firm are generated randomly in accord with a Uniform distribution $U[C_{\min}, C_{\max}]$. Also, firms' initial costs are generated randomly in accord with a Uniform distribution $U[50, 150]$. The setting of these parameters indicates that the environment is of high uncertainty and the firms are of high variety. The number of runs (i.e., demand cycles) of the simulation is set as 100, and each demand cycle stands for one month in the real world.

3.2.1. Experiment 1: Evolving structure of SNs

There are two experiments (a and b) in experiment 1, where the eight firms adopt the cost-priority strategy, and the firm with the lowest bidding price wins the remaining demand at the second stage. Firms' bidding prices are generated by a price function as $p_i = (1 + \beta_i)C_i$, where p_i is firm$_i$'s price, C_i is firm$_i$'s cost, and β_i is generated randomly in accord with a Uniform distribution $U[0,1]$. The other test parameters are set as: $F_c = 0.35$, $D_{\min} = 5000$, $D_{\max} = 10{,}000$, $C_{\min} = 25$, and $C_{\max}$ is calculated such that the mean cumulative firm capacities is 95% of $D_{\max}$. The initial fitness of the eight firms is generated randomly, which is in accord with a Uniform distribution $U[0.40, 0.75]$. The decay speed of firm's fitness is 1% in each demand cycle. The decay speed $\Delta\delta_i(t)$ at each cycle is 1%.

In experiment 1(a), the eight firms make product 1 without subparts. In experiment 1(b), they make product 2 which has two parts. Each firm can make the two parts and assemble them into the final product. Once a firm wins the demand of the final product in the first stage, it makes decisions on: (1) manufacturing the whole product by itself; (2) subcontracting the whole product to other firms; (3) subcontracting the parts and assembling the parts into the final product by itself. The solution with the lowest total cost among the three choices will be selected.

(1) *Emergence:* In experiment 1(a), a linear structure SN emerges from the interaction of the eight firms for the fulfilling of the stochastic demand. In the 0th demand cycle, there is no relationship at all among the firms. However, with their competition and collaboration, a linear structure SN emerges in each demand cycle and the SN structure evolves over time (see Fig. 2). In the 98th demand cycle, firm 0 subcontracts its remaining demand to firm 1, and firm 1 subcontracts some of the order to firm 2. This linear structure SN evolves into a new structure which includes firms 1, 0, and 5 in the 99th demand cycle, and further evolves into a new linear structure SN including firm 5, 0, 1 and 2 in the 100th demand cycle. In experiment 1(b), there not only emerges the linear structure SNs (see Fig. 3a), but also emerges SNs with a binary tree structure (see Fig. 3b).

Experiment 1 indicates that different SNs emerge and evolve with the dynamic interaction among firms without anyone's control. A linear-structure SN emerges when firms make product 1. But when a more complex product (Product 2) is involved, various SNs emerge and evolve over time. Some SNs are of high horizontal complexity, while some are of high vertical complexity. The complexity of the SN is related to the internal mechanisms of firms (e.g. product structure, fitness, cost, capacity, strategy), and the environment elements (e.g. F_c, market structure, demand).

(2) *Path-dependence:* As shown in Fig. 4, when the firms collaborate to make product 1, the firm 0 subcontracts the remaining demand to the firm 4 for 56 times in the 100 demand cycles, firms 3 subcontracts the

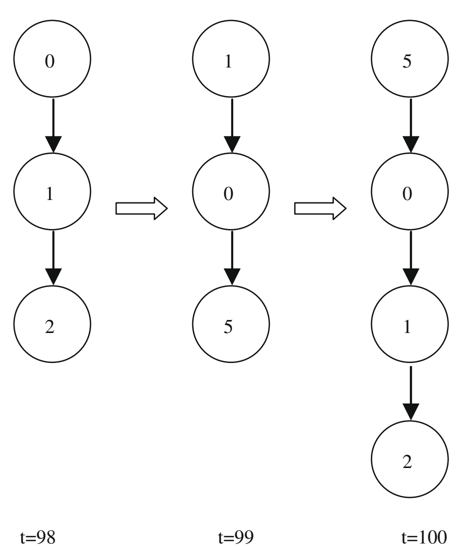

Fig. 2. SN emergence and evolution (Product 1)*.

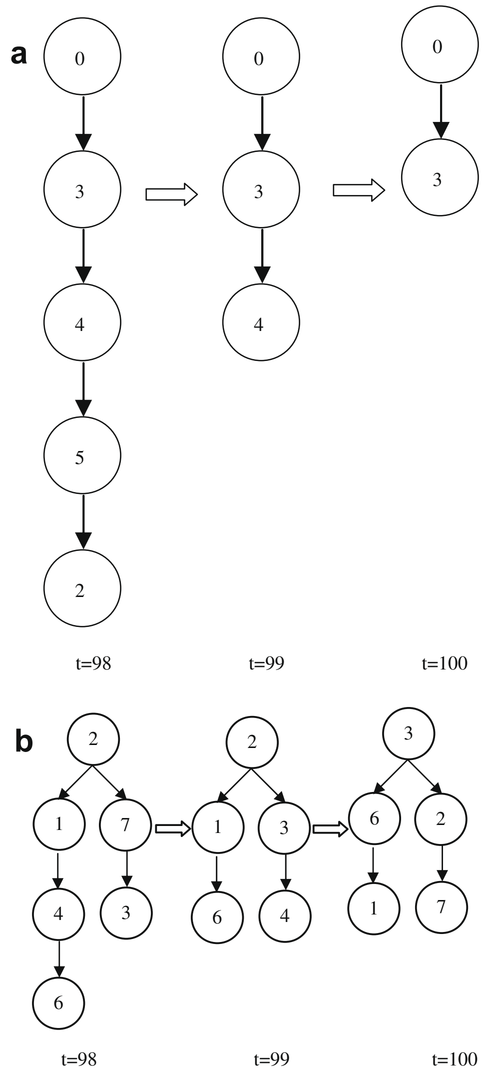

Fig. 3. The emerged SN with various structures (Product 2).

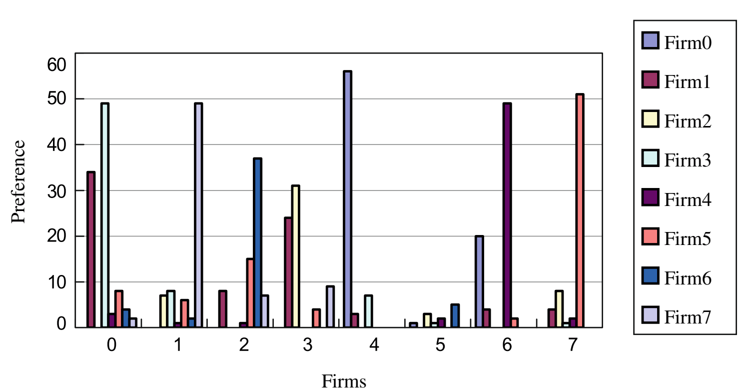

Fig. 4. Path-dependence.

remaining demand to the firm 0 for 49 times, and the firm 5 subcontracts to the firm 7 for 51 times, etc. Those firms who form a mutually compatible collaboration structure survive, and the survivors lock-in their partners. The collaboration is self-reinforcing, and path-dependent.

(3) *Multiple equilibrium and chaos:* As we repeat experiment 1(a) for 100 times, we find four kinds of evolution patterns (see Fig. 5) which are dramatically different. As shown in Fig. 5(a), the fitness of the 8 firms degrades gradually. Firm 0 dies at the 36th demand cycle, and all the other firms die gradually. Finally, all the firms die at the 93rd demand cycle. On the contrary, the fitness of the 8 firms increases over time and the collaboration evolves into a win-win pattern (see Fig. 5(b)). All the firms survive and thrive, and their collaboration achieves a superior equilibrium. In Fig. 5(c), some firms' fitness increases while some declines over time. Those firms that their fitness below F_c are eliminated from the environment, which further results the network structure evolves dynamically over time. In Fig. 5(d), the fitness of firm 6 decreases gradually in the first 71 demand cycles and falls in an inferior path. But in the 72nd cycle, it gets the remaining demand with the lowest price, and fulfills the demand successfully. Further, firm 6 escapes from the inferior path and its fitness increases in the following cycles. In the repeated simulations, we find that most of the evolution patterns match Fig. 5(c). However, at the beginning of the experiment, it is difficult to predict which pattern will emerge, although the experiments setting are the same. The various evolving patterns of SNs indicate that the evolution has multiple equilibrium states. It is highly sensitive to the initial conditions. Some initial conditions may drive the SN to evolve into a superior equilibrium and achieve system efficiency. While some may drive the SN to fall into an inferior equilibrium with system inefficiency. Any slight difference in the initial conditions may drive the evolution into totally different patterns. There is non-deterministic chaos in the evolution, which cannot be predicted precisely.

3.2.2. Experiment 2: Stability of SNs

In Experiment 2, the stability of the evolving SN is studied. Except for F_c, $\Delta\delta_i(t)$ and firms strategies, the other parameters are the same as experiment 1, and the 8 firms make product 1. There are two steps in the experiment.

(1) At first, we test the stability of the evolving SN in different environments where F_c is different ($F_c = 0.25$ and $F_c = 0.40$). The eight firms adopt the price-priority strategy. The decay speed of the of $\Delta\delta_i(t)$ at $F_c = 0.40$ is 1.6 times to the speed at $F_c = 0.25$. The highest weight of collaboration preference in a SN is used to evaluate the stability. If the weight is small, it indicates that the firms change their partners frequently and the SN structure varies over time. Otherwise, they lock-in their partners and the SN structure is stable. The means and the standard deviations of the data are shown in Table 1. The Hypothesis 1 is made.

Hypothesis 1. In different environments, the stability of a SN is different.

(1) Secondly, we analyze the influence of firm's strategy on the stability of the SN in the same environment ($F_c = 0.25$). At first, the 8 firms adopt the short-term strategy. And then, the 8 firms adopt the long-term strategy. With the short-term strategy, the decay speed of $\Delta\delta_i(t)$ is twice to the decay speed as firms holding the long-term strategy. The tenderee firm subcontracts the remaining demand to the other firms whose *attraction* is the highest. In the short-term strategy, the attraction is decided by Eq. (9), where the bidder's *collaboration preference* with the tenderee in the history is weighted 25%, and the price is weighted 75%. In the long-term strategy, *attraction* is calculated by Eq. (10). The *collaboration preference* and *price* are normalized into [0, 1]. The difference of the weight on collaboration preference represents the influence of the social factors (e.g., culture) and firm's preference on collaboration strategy. The means and the standard deviations of the data are shown in Table 2. The Hypothesis 2 is made.

$$attraction = 0.25\ collaboration\ preference + 0.75\ price \quad (9)$$

$$attraction = 0.75\ collaboration\ preference + 0.25\ price \quad (10)$$

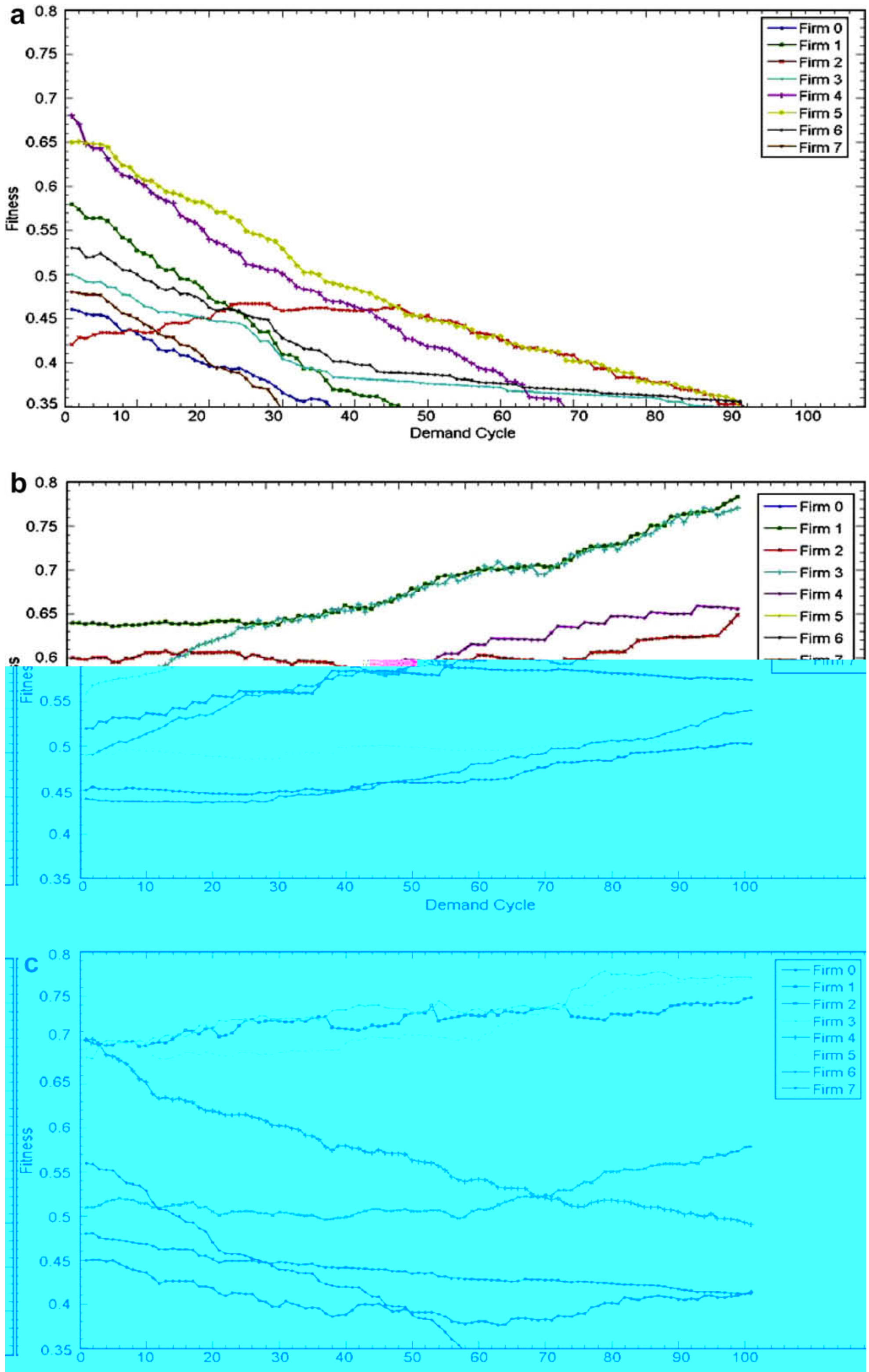

Fig. 5. Multiple equilibrium and chaos in the SN evolution.

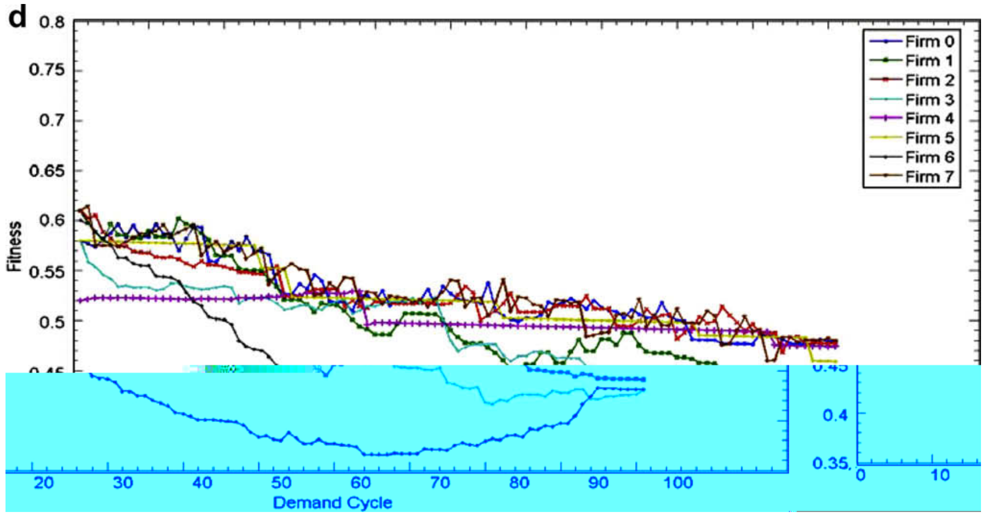

Fig 5. (*continued*)

Table 1
Independent sample t-test of the means of the collaboration preference

Environment	Sample size	Mean	Standard deviation	P-value
$F_c = 0.25$	30	69.73333	13.40852	0.176
$F_c = 0.40$	30	63.56667	20.59743	

Table 2
Independent sample t-test of the means of the collaboration preference

Firms' strategy	Sample size	Mean	Standard deviation	P-value
Long-term strategy	30	94.70000	5.73044	0.000
Short-term strategy	30	79.03333	17.75792	

Hypothesis 2. A SN's stability is different when the firms adopt different strategies.

We used the software package SPSS to analyze the data. At first, the data in Tables 1 and 2 is proved that they are subjected to the normal distribution. And then, an independent samples t-test is used to test the difference between the means of the data. The result is shown in Tables 1 and 2. The reject of Hypothesis 1 indicates that once there emerges a mutually compatible SN, it keeps stable. In the real world of low uncertainty the driving force of a manufacturer to change suppliers is low when the suppliers can fulfill orders as required. On the other hand, in a volatile environment, the transaction cost is too high to change partners frequently. Therefore, once firms find their mutually compatible partners, they lock-in each other and collaborate path-dependently.

Hypothesis 2 is accepted. Furthermore, we can prove that a SN is more stable if the partners adopt the long-term strategy. In the real world, the long-term collaboration relationship helps the partners to foster trust and decrease the transaction cost. For example, TOYOTA builds the 'Keiretsu' to manage the collaboration activities with its suppliers. They forge long-term collaboration relationship and achieve the world-class manufacturing. DELL adopts the VMI (vendor-managed-inventory) schema with its suppliers. Long collaboration boosts DELL evolving into the No. 1 personal computer manufacturer, and its suppliers (e.g. Flextronics, FOXCONN) become the world-class EMS (electronic manufacturer suppliers). The long-term relationship reinforces the winner-take-all effect in the collaboration, which results in more difficulties for new firms to join in the SN, and reinforces the path-dependence effect.

3.2.3. Experiment 3: Fitness evolution

In Experiment 3, we compare the evolution of firms' fitness as the firms adopt different strategies. (1) The 8 firms adopt the short-term strategy; (2) the 8 firms adopt the long-term strategy. The other parameters are the same as those of experiment 2. We repeat the simulation for 30 times and the means and the standard deviations of the fitness of the 8 firms are shown in Table 3. We have *Hypothesis* 3:

Hypothesis 3. The variance of the firms' fitness in the evolution is different when firms adopt different strategies in the same environment.

At first, the data in Table 3 is proved that they are subjected to the normal distribution. And then, an independent samples *t*-test is used to test the means of the data. *Hypothesis* 3 is accepted. Furthermore, we can prove that the long-term collaboration strategy is better for the firms to improve their fitness. In practice, many firms achieve high performance by adopting the long-term collaboration strategy. For instance, Chrysler adopted the short-term strategy in SN collaboration in the early 1980s. Suffered from the high procurement cost and the long lead-time in the SN collaboration, Chrysler fell into the edge of bankruptcy. To survive, Chrysler had to move to the long-term collaboration strategy in the SN management. In 1989, Chrysler forged long-term contracts with its partners and implemented the SCRE (Supplier Cost Reduction Effort) plan to help the suppliers to reduce cost, to share information, etc.. Consequently, suppliers' performance, the manufacturing cost, delivery time, and product R&D (Research and Design) time of Chrysler were all improved greatly. Chrysler survived and thrived at the edge of chaos.

4. Case study

CHINT Group Co. is a LVEA (low-voltage electric apparatus) manufacturer in China and the largest firm in the Wenzhou city, Zhejiang province, the southeast of China. Zhejiang province has been the freest market since 1970s when the government began the market economy reform. In the past 30 years, CHINT SN emerged, adapted, and evolved into a huge network, which involved the final assembler (CHINT), 786 first-tier suppliers, and more than 3000 second-tier suppliers in the year of 2005. The distribution network had three tiers: 11 first-tier regional distribution centers, 31 second-tier provincial sales offices, and more than 2000 third-tier sales agencies in small counties of China. Besides, CHINT had 5 sales offices and 30 sales agencies outside China. In 2005, the total annual sale of CHINT Co. was RMB15 billions.

The evolution of CHINT SN involves three stages: emergence, development and maturity (see Fig. 6). The qualitative traits of the evolution can be captured by the dimensions of physical structure (product, network), technology (product, process, information sharing), strategy (business objectives, operation strategy), and organization (formalization, centralization) (Carbonara et al., 2002; Choi & Hong, 2002).

In the emergence stage, the SN was characterized by the "casual-vertical-dependent collaboration schema". In 1984, encouraged by government's free market reform, more than 1000 firms were founded to make single LVEA in Wenzhou city. And the mother firm of CHINT, called QJ, was one of them. The homogeneous products that were of low complexity on product structure and technology fostered intensive competition in the local market, which forced QJ to adopt the "make-to-order" strategy, built its plant and founded more than 1000 sales offices to get more demand. The great demand exacerbated the scarce of the internal capacity of CHINT and it had to adopt the "buy to order" strategy and subcontracted surplus demand to other firms. For partner selection, cost was the overarching force that shaped the SN. Subcontractors were only viewed as passive doers for the supplement of CHINT's internal capacity. The collaboration was short-term oriented and always based on oral agreements. To reduce cost, CHINT frequently changed suppliers, which resulted

Table 3
Independent sample t-test of the means of the fitness variance

Firms' strategy	Sample size	Mean	Standard deviation	*P*-value
Long-term strategy	30	0.0588990	0.16921757	0.044*
Short-term strategy	30	−0.0463550	0.22303856	

* The significance is 0.05.

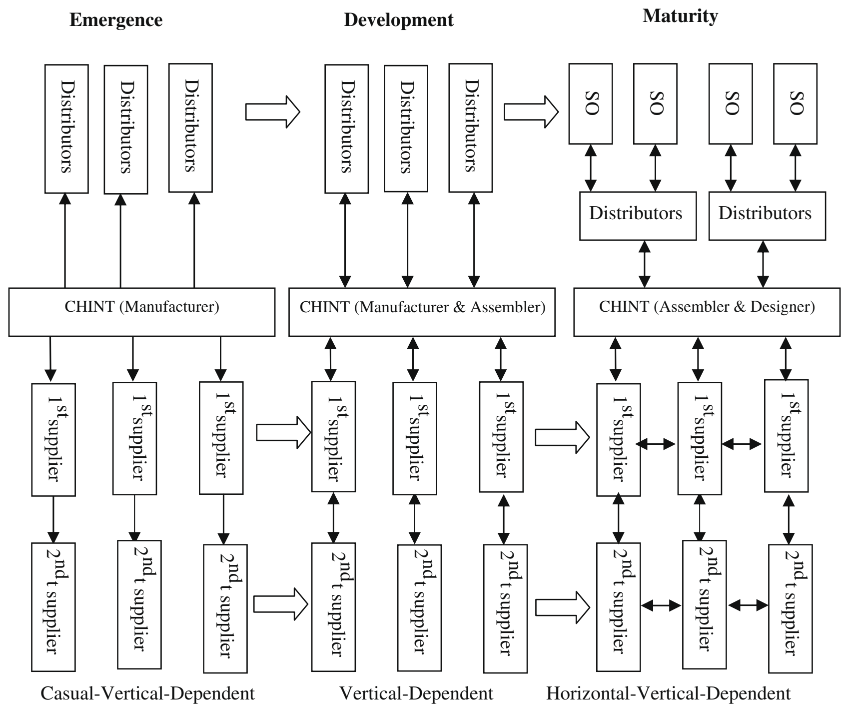

Fig. 6. Evolution of CHINT SN.

the great number of the suppliers in the same tier and the varying structure of the SN. The intensive competition further boosted QJ's improvement on product quality. In 1990, the government closed 1268 firms with poor quality products and issued production licenses to qualified firms. QJ was one of these firms and got a great progress at that year. In 1991, QJ was splited into 2 firms, and one of them was CHINT.

From 1994 to 2000, the CHINT SN evolved into the development stage, which was characterized by the "vertical-dependent collaboration schema", where the horizontal and vertical complexity, the centralization and formalization of the SN became higher than those at the emergence stage. In 1994, CHINT moved to a new strategy that focused on differentiation, quality and flexibility. It began to make the whole set of LVEA which was of higher complexity in structure and technology. This resulted the increasing of the horizontal and vertical complexity of the SN, and the vertical dependence among firms in different tiers. To innovate products, improve cost, quality and flexibility, CHINT moved to the "make-to-order" and "assemble-to-order" strategy. It bought 48 local firms and founded the CHINT Group Co. Those firms with the same products' families were merged into seven key parts suppliers. CHINT only made 10% key parts in-house and subcontracted 90% parts and sub-assembly to other firms. CHINT forged long-term relationships with the suppliers, implemented the "Grand CHINT Plan" and the "Second Party Quality Certification Plan", and routinely exchanged the market and technology information with the suppliers. The collaboration became more centralized, and the SN became more stable.

Since 2000, the CHINT SN has been evolving into the maturity stage, which is characterized by the "horizontal-vertical-dependent collaboration schema". The intensified product differentiation and the movement to the "assemble-to-order" and "design-to-order" strategy resulted the higher level of horizontal and vertical complexity of the SN, the horizontal dependence among suppliers at the same tiers, and higher level of centralization and formalization. CHINT began to design and assemble the whole set high-voltage electric apparatus, which were more complex than LEVA. The increasing complexity of products resulted the higher vertical and horizontal complexity of the SN, and it further enhanced the horizontal dependence among suppliers at the same tiers by the horizontal subcontracting in the same tier. Also, the market internationalization exacerbated the complexity of the distribution network. To improve product, cost, quality, technology, and reduce suppliers, CHINT implemented the supplier-bidding mechanism, some incentive mechanisms, long-term contract, supplier performance assessment, and operation information sharing with suppliers. It also helped suppliers to improve technology and management. These exacerbated suppliers' reliance on CHINT and reinforced the centralization and formalization of the SN.

5. Results of the study: propositions and managerial implications

From the above simulations and case study, we propose the following propositions.

Proposition 1. *The economic policies, government regulations, and industry structures influence the evolution of a SN from the external environment.*

Firms collaborate to fulfill the demand generated in the environment. The changing of the economic policies, government regulations, and industrial structure has influence on firms' dynamic interaction. Those firms adapting to the environment survive and grow up. Those firms who could not adapt to the environment are eliminated by the environment. Furthermore, more firms competing in the market lead to more intensive competition, and further boost the evolution of the SN.

Proposition 2. *Firms' strategies, product structure complexity, technology complexity, quality and cost considerations involved in the internal mechanisms of firms are the internal dominated forces to shape the SN evolution.*

A SN emerges and evolves with the process of partner selection and their collaboration pattern afterwards. A firm's different strategies result different complexity in product structure and technology, which are the salient architects in the construction of a SN. Firm's consideration of cost and quality affects how firms select suppliers, and further influences the stability, centralization and formalization of the network.

Proposition 3. *The dynamic interaction of the environment factors and the internal mechanism factors results that the evolution of a SN is highly sensitive to the initial conditions. The evolution of a SN is path-dependent. Slight perturbation of the environment and the internal mechanism of firms can drive the evolution into chaos, and it is difficult to predict precisely.*

Firms have to adapt to the environment, and try to know, trust, connect and collaborate with others in routine. At the same time, the costs of searching for new partners are reduced by focusing on and working more closely with the previous connected firms. However, SNs that are too richly connected are in danger of producing chaotic behavior that adversely affects the SNs to evolve effectively into a super equilibrium. Too many parts of the SNs are affected by any change, resulting in the difficulty to predict precisely.

The implications for management of this are that managers should not only investigate the dynamics behavior of firms, but also should investigate the SN as a whole. To better manage the SN, managers and policy makers should use the order parameters for enacting large-scale change. For policy makers, it is better to develop institutions which are beneficial to firms' collaboration, rather than to control firms' operations directly. Managers should learn how to adapt to the environment and form a mutual compatible SN to improve their fitness to the environment. Any incorrect assumptions about the SN by managers and policy makers can lead to unintended consequences due to the continuously evolving nature of the SN. Policy makers and managers should learn how to balance between control and emergence.

6. Conclusion

The review on supply chain management identified a gap in the study of the evolution of supply networks due to the absence of knowledge of the dynamics of the network structure, collaboration mechanism and the environment. This paper proposed an evolution model of SN based on CAS and fitness landscape theory to gain understanding of the evolution of the SNs. The simulation of the evolution model and the case study indicated that the evolution of SN is self-organizing. An SN emerges from the dynamic interactions among the firms and evolves over time. The evolution is self-reinforcing and path-dependent. Slight perturbation of the environment and the internal mechanism of firms can drive the evolution into chaos and it is difficult to predict. The environment and the internal mechanisms of the firms are the origins of the self-organization evolution of a SN.

Several aspects of the evolution of SN warrant further investigation. Our present research directions include (1) incorporation of more adaptive firms that are capable of modifying their collaboration strategies during simulation based on the evolving environment; (2) incorporation of the dynamics of the environment that are capable of changing F_c to model the dramatic changes of the environment. For instance, as a disaster happens, F_c may be changed greatly; and (3) development of an evolution model of service supply chain, which is of great difference to the traditional supply networks.

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