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The evolutionary complexity of complex adaptive supply networks: A simulation and case study

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ABSTRACT

A supply chain should be treated not just as a supply chain but also as a complex adaptive supply network (CASN). However, the literature on supply chain management has given little attention to the evolutionary complexity of the network structure and collaboration mechanism of CASNs. In this paper, we first model and simulate the evolution of CASNs based on complex adaptive system and fitness landscape theory. The simulation results indicate the evolutionary complexities such as emergence, quasi-equilibrium, chaos, and lock-in of CASNs. Then, a case study of the evolution of the LVEA (low voltage equipment apparatus) supply network in the emerging Chinese market has been explored to validate the findings from the simulation and develop a better understanding of the general principles influencing the emergence, adaptation and evolution of CASNs in the real world. Based on the simulation and the case study, we propose some propositions about the factors and principles influencing the evolutionary complexity of CASNs. The external environment factors and firm-internal mechanisms appear to be the dominant forces that shape the gradual evolution of CASNs. Factors in the external environment, such as government regulation, market demand and market structure appear to have a long-term impact on the evolution, while a firm's strategies, product structure, technology, and organization appear to be the internal factors that exert an immediate influence on the evolution of CASNs. Among these factors, cost and quality considerations appear to be the primary forces that influence the structure complexity, centralization and formalization of CASNs.

1. Introduction

A supply chain is a network of autonomous or semiautonomous business entities collectively responsible for procurement, manufacturing and distribution activities, which create value for final customers in the form of one or more families of related products or services (Christopher, 1992; Min and Zhou, 2002; Swaminathan et al. 1998). Firms with highly synchronized supply chains have a number of advantages in today's highly competitive, fast-changing environment. One of the major challenges for supply chain managers is to develop a network structure and collaboration mechanism that can facilitate adaptive, flexible and synchronized behaviors in a dynamic environment. However, researchers are still in the early stages of investigating the general principles that govern the birth, growth and evolution of supply networks with complex network structure and mechanisms for collaboration. A key to tackling this problem successfully is the realization that supply chain should be treated as a complex adaptive supply network (CASN).

Pathak et al. (2007a) proposed that a CASN be viewed as a CAS (complex adaptive system) consisting of interconnected autonomous entities that make choices concerning adaptation and survival. And as a collective, the system evolves and self-organizes over time, in response to changes in its environment. The concept of CASN allows us to understand how supply chains, considered as living systems, adapt to, and co-evolve with, the rugged and dynamic environment in which they exist, and to identify patterns that arise in such a condition of co-evolution (Surana et al., 2005). In a CASN, different entities operate subject to different sets of constraints, each with their own local objectives, and each, with different local views of the environment. With their interaction, these entities sense, learn, and adapt to the environment. The CASN is a highly nonlinear system, which shows complex multi-scale behavior, and has a dynamically evolving organizational structure and collaboration pattern for a given product. A similar viewpoint has been presented by Choi et al. (2001), who sought to demonstrate how supply chains should be managed if we recognize them as CASs. However, no

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concrete framework has been suggested under which such conjectures could be verified and generalized (Surana et al., 2005).

The goal of this study is to identify the general principles and the salient factors that govern the evolution of CASNs. Based on an understanding of the operation of CASNs in the real world, this paper proposes a model for CASN evolution using the principles of CAS and fitness landscape theory. Based on a simulation of the model and a case study, some general principles concerning the evolutionary complexity of CASNs are proposed, together with their managerial implications.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the evolution model of CASNs. Section 4 presents the simulation of the evolution model and identifies some salient factors and principles influencing the evolution. In Section 5, a case study is conducted to validate the findings of Section 4. In Section 6, we present some propositions concerning the evolutionary complexity of CASNs. In Section 7, the main contributions of this study are summarized, and some of its implications for management are identified. Finally, concluding remarks and future research directions are set forth in Section 8.

2. Literature survey

A CASN is a distributed network which is inherently difficult to understand due to its evolving structure and functions, the diversity of its connections, the dynamic complexity of its constituent entities, and the interactions among all these factors. In order to study a CASN as a whole, it is critical to understand the nature of the interplay between its structure and its functioning (Surana et al., 2005). The structural issue focuses on the decision about the nodes in the network and the related linkages. The functional issue concerns the "collaboration" between the nodes. Effective CASN management requires "consistency" or "fit" between network structures and collaboration patterns (Hur et al., 2004; Fisher, 1997; Ramdas and Spekman, 2000; Lee, 2002; Stock et al., 2000).

Over the past decade, numerous studies have enriched our understanding of the issues related to CASNs (Beamon, 1998). Analytical models, simulations methods, and empirical approaches have all been used to probe supply networks from both strategic and operational level. Most of the analytical studies have focused on the design and optimization of the operation decision of supply networks based on the assumption that a supply network is an integrated, static organization (Min and Zhou, 2002; Gunasekaran and Ngai, 2005; Whang, 1995). Although specific results can be obtained from analytical models via proofs or bounds, the analytical models for supply networks are often limited in their ability to map the dynamics of the system and obtain solutions for problems of reasonable size (Pathak et al., 2007a). Most supply networks are large-scale systems consisting of numerous entities and inter-connections among entities, and where the entities and connections are continuously evolving.

Computer-based simulations have been used both to investigate the complexity of CASNs and to support real world decision-making for actual supply networks. Simulation is a powerful tool for investigating the behavior of large-scale systems which are analytically intractable, and for examining various decisions for the improvement of a given supply network. Forrester (1961) was the first to use system dynamics-based simulation to examine dynamic behavior of a supply chain. Since then, illuminating results have been generated by this line of research (e.g. Berry et al., 1995; Larsen et al., 1999; Marquez and Blanchar, 2004; Swaminathan et al., 1998; Towill, 1996; Towill et al., 1997; Wikner et al., 1991). Although system dynamics-based simulation can be used effectively to examine the internal complexity of a supply network for a given structure, it is difficult to model the dynamic evolution of such a network because it is still based on the assumption that the structure of a supply network is static or fixed. In the real world, however, as a result of changes in markets, technology, and products, among other things, the structures of CASNs are always evolving. Therefore, regardless of the increasing amounts of time and money spent, efforts based on the static structure assumption and using the analytical models and system dynamics simulation approaches, often lead to frustration and helplessness (Choi et al., 2001).

To better understand and manage CASNs, researchers and managers need to examine their complex nature from an evolutionary perspective. They need to address questions such as: how does a CASN emerge, adapt and evolve over time? What general factors and principles govern the evolution of the structure and the collaborative mechanisms of CASNs? Since the seminal contribution on supply chains as CAS by Choi et al. (2001), other studies on the evolution of supply networks have appeared. Choi et al. (2001) put forth various conjectures regarding how the patterns of behavior of individual entities in a supply network relate to the emerging network and the evolutionary complexity of a CASN. Surana et al. (2005) proposed that the concepts-tools and techniques used in the study of CASs could be exploited to characterize and model supply networks. Wilkinson and Young (2002) argued that network structure and behavior emerge through the local interaction of network members in a bottom-up self-organizing way. Pathak et al. (2007a) provided a good review of CAS studies, raising some critical issues and posing some important challenges for CASNs. Although a number of conjectures were proposed, no concrete framework or method was suggested for verifying them.

In recent years, a number of simulation-based and empirically based investigations of the evolutionary dynamics of CASNs have appeared, some of which have focused on the operational level. For instance, Adamides and Pomonis (2007) suggested that a firm's manufacturing strategy may emerge as a result of a coordinated search in the three correlated fitness landscapes of product, production, and supply chain decisions. Alfaro and Sepulveda (2006) found that flexible production systems may demonstrate chaotic behavior. In linear supply chains, there are signs of non-linear behavior such as phase transitions and chaos (Nagatani and Helbing, 2004). The deterministic chaos in a three-tier supply chain emerges from the interaction between customers and suppliers (Wu and Zhang, 2007). Holweg and Bicheno (2002) used a participative simulation model to demonstrate supply chain dynamics and to model possible improvements to a supply network. However, none of these studies provides any insight into the understanding of the dynamics of the network structure and collaboration pattern of a CASN from the strategic perspective.

In fact, only a few studies have been carried out on the dynamic structure, evolution and behavior of CASNs and they have proposed inconsistent conclusions. Some of those studies were based on multi-agent modeling and simulation techniques. Agent-based models can be used to explore various emergent network phenomena, such as, how the behavior of firms and the supply network evolve under different conditions. For example, Eymann et al. (1998) developed a multi-agent based system for the simulation of the trade network and proposed that the trade network grew out of the developing cooperative relationships between firms. Pathak and David (2002), Pathak et al. (2002, 2003, 2007b) developed a multi-agent based simulator and showed that certain environmental and firm-level factors have an influence on the eventual evolution of CASN structures. In addition to the studies of the dynamics of network structure, there has also been