Physica A 489 (2018) 141–148

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Exploring the evolutionary mechanism of complex supply chain systems using evolving hypergraphs

Qi Suo [a,b], Jin-Li Guo [a,*], Shiwei Sun [c], Han Liu [d]

[a] Business School, University of Shanghai for Science and Technology, Shanghai, 200093, China
[b] School of Economics and Management, Qingdao University of Science and Technology, Qingdao, 266061, China
[c] Raymond J. Harbert College of Business, Auburn University, Auburn, AL 36849, USA
[d] Trade and Technology Department, XiJing University, Xian, 710123, China

HIGHLIGHTS

- A model is proposed to describe the evolution pattern of supply chain systems.
- The model is analyzed by using the Poisson process theory and continuum theory.
- Numerical simulations are given for different parameters on the model.

ARTICLE INFO

Article history:
Received 28 July 2016
Received in revised form 6 April 2017
Available online 7 August 2017

Keywords:
Supply chain systems
Complex network
Evolving hypergraph

ABSTRACT

A new evolutionary model is proposed to describe the characteristics and evolution pattern of supply chain systems using evolving hypergraphs, in which nodes represent enterprise entities while hyperedges represent the relationships among diverse trades. The nodes arrive at the system in accordance with a Poisson process, with the evolving process incorporating the addition of new nodes, linking of old nodes, and rewiring of links. Grounded in the Poisson process theory and continuum theory, the stationary average hyperdegree distribution is shown to follow a shifted power law (SPL), and the theoretical predictions are consistent with the results of numerical simulations. Testing the impact of parameters on the model yields a positive correlation between hyperdegree and degree. The model also uncovers macro characteristics of the relationships among enterprises due to the microscopic interactions among individuals.

1. Introduction

Traditionally, supply chains are viewed as simple linear systems interacting through a chain of dyadic relationships linking suppliers to end users. However, in order to adapt to today's complex and changeable business environment, there is now a need to re-conceptualize the structure of supply chains from simple linear systems to complex adaptive systems [1,2]. To describe the characteristics of supply chain systems, scholars use methods such as analytical models, simulation methods, and empirical approaches to explore supply chain systems at both the strategic and operational level [3–5]. Some models are often based on network theory [6], where the network incorporates a set of nodes and edges that represent the individual enterprises and the connections amongst them. To create products or services, enterprises engage in reciprocal relationships

* Corresponding author.
E-mail address: phd5816@163.com (J. Guo).

http://dx.doi.org/10.1016/j.physa.2017.08.002
0378-4371/

with others in the network, which take the form of various types of flows such as material flows, information flows and financial flows.

Recently, supply chain management has begun to engage with the literature of complex supply chain networks [7]. Building on the work of Nair and Vidal [8], who extended the linear supply chain context to a complex supply network, Hearnshaw and Wilson [1] used a complex network model to represent the structure of efficient supply chains, and found that real supply chain systems are similar to scale-free networks. Kühnert et al. [9] also found that a city's material supply network obeys a scale-free distribution. To understand how supply chain systems grow, evolve and adapt, others have suggested using dynamic models to identify the reasons behind the supply chain systems dynamics reported by these researchers. For example, Xu et al. [10] established a model to describe the growth process of an agile supply chain network and Li et al. [11] modeled and simulated the evolution of complex adaptive supply networks based on complex adaptive system and fitness landscape theory, while Ge et al. [12] developed an evolutionary decision-making model to characterize the effects of suppliers' altruism in supply networks.

Although all the above have contributed to our understanding of supply chain systems, complex networks based on simple graphs are no longer capable of providing a complete description of these real-world systems due to the highly diverse edge types and the complexity of the network structures involved. Some scholars tried to generalize supply chain networks into network-based Supernetworks. A supernetworks is a 'network of networks' [13], which was first proposed by Denning in 1985. Nagruney et al. [14] further elaborated that supernetworks were suitable to deal with supply chain systems including financial, informational, and logistical flows. Nowadays, Cheng et al. [15,16] proposed the concept of supply–demand matching hypernetwork of manufacturing services. Another possible solution to this dilemma is to utilize hypergraph theory, as it provides a useful way to investigate the topological characteristics of social networks and should thus also serve as an effective tool for modeling complex supply chains systems. The topological properties and evolving models based on evolving hypergraphs will also be discussed.

In practice, supply chain systems are dynamic. With the number of enterprises and the linkages among them constantly changing, they evolve over time. Given the need to capture these important properties, is it possible for a model to adequately depict the underlying structure, formation and evolutionary mechanism of a supply chain system? The main objective of this paper is to answer this question by providing an in-depth examination of the evolutionary mechanism of complex supply chain systems. The nodes are treated as arriving according to a Poisson process, and the evolving process incorporates the addition of new nodes, the links among old nodes and the rewiring of links. This re-conceptualization provides the theoretical basis for the further development of supply chain network theory.

The remainder of this paper is organized as follows. Section 2 explains the theory and concepts of hypergraphs. Section 3 describes the construction of a model incorporating the addition of new nodes, linking among old nodes and the rewiring of links. Section 4 presents the theoretical analysis based on the Poisson process and continuum theory. Section 5 shows the simulations and tests the effects of the model parameters. Section 6 discusses the results and suggests some potentially fruitful directions for future research.

2. Theoretical background

The underlying structure of complex networks is generally treated as a set of simple graphs, but this fails to provide a complete description of dynamic real-world systems such as supply chains. A more natural way of representing these systems is to use a generalized form of graphs known as hypergraphs [17,18]. The hyperedge of a hypergraph can contains arbitrary number of nodes and can thus represent the interactions among a variety of nodes more effectively. Extending the concepts of complex networks, hypergraphs can be created that provide a better representation of complex systems [19].

The first application of hypergraphs for representing social networks appeared in 1981 as reported by Seidman [20]. Recently, scholars have begun to discuss the characteristics in more detail. Estrada and Rodríguez–Velázquez [19] extended the concepts of subgraph centrality and clustering coefficient and applied the results to an empirical analysis of three real world datasets, while Ghoshal et al. [21] proposed a mathematical model for random hypergraphs and compared the results with data from the Flickr folksonomy. Topological characteristics such as node superdegree, superedge–superedge distance, and superedge overlap were discussed by Ma and Liu [22]. Xiao [23], Kapoor et al. [24], Ma and Liu [22] proposed a new multi-criteria measuring method, weighted node degree centrality and Superedgerank algorithm, respectively, to identify the key nodes in networks; and Criado et al. [25] defined the concept of hyperstructure and calculated the efficiency of the associated network. Other research in this area has considered aspects such as community detection, synchronization, cascading failure, collaborative recommendation and so on.

Constructing evolving models to depict complex systems has also drawn the attention of scholars. For example, Wang et al. [26] proposed a dynamic model based on growth and preferential attachment mechanisms, in which several newly added nodes, together with one existing node, form one hyperedge. Hu et al. [27] took a different approach: in their model, at each time step there is only one newly added node and multiple old nodes are selected to construct a new hyperedge. Guo and Zhu [28] proposed a scale-free model unifying these two models that could be degenerated to the classical BA model. Besides the above basic mechanisms, evolving models that are based on different preferential attachment mechanisms such as joint degree [29], nonlinear preferential attachment [30], and hyperdegrees with brand effect and competitiveness [31] have also been proposed. As microscopic events may also affect the evolution of networks, local-world models [32], connections among old nodes [33] and the influence of aging [34] have also been investigated.