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# Three-dimensional-flow model of agent-based computational experiment for complex supply network evolution

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ABSTRACT

The current literature about supply network evolution mainly focuses on the network structure dynamics. Its evolution models are too abstract. Set with theoretical parameters, they aim to discover the general evolution laws of supply networks, but the value of their research results in practical applications is weakened. Considering the features of complex supply networks, this paper builds the evolution model in the three dimensions of material, information, and time flows, and adopts a new methodology—agent-based computational experiment (Long, 2014) to implement the evolution model. In this paper, a three-dimensional-flow model and its modeling approaches are proposed. In this model, the approaches for static structure modeling and dynamic evolution modeling are given to support building the material flow model. A general approach for order hierarchical decomposition based on product process, and a coordination solution for agents' consistent knowledge understanding based on public and private ontology with partial information sharing are presented in the information flow modeling. To support collaborating time flows of agents in a distributed and heterogeneous virtual environment, a time flow collaboration scheme based on decoupled model and asynchronous parallel is proposed. The scheme not only ensures the event causality in the virtual world consistent with that in the real world, but also improves the efficiency of the agent-based computational experiment of supply networks to a great extent. In addition, this paper integrates the three-dimensional-flow model for supply network evolution into a reference architecture of agent-based computational experiment, and discusses the implementation solutions of its multiple layers. The architecture provides a more valuable reference to the three-dimensional-flow model implementation as well as the related studies.



## 1. Introduction

Composed of multiple enterprises, supply network is featured by the typical complex adaptive system (Nair, Narasimhan, & Choi, 2009) which transforms raw materials into products and delivers them to customers. It is no longer a single chain but a network intertwined with a few chains (Fasli & Kovalchuk, 2011; Lin & Wang, 2011; Mizgier, Wagner, & Holyst, 2012; Xu, Liu, & Wang, 2008). In the network, enterprises play different roles in different chains, such as supplier, manufacturer or something the like. These complex supply networks are quite common in manufacturing and service industries. Compared with the traditional supply chain, the supply network has more realistic backgrounds. It shows distinctive features that enterprises are geographically distributed with heterogeneous information systems and share partial information with others. These features bring a new greater challenge to study supply network evolution. Supply network is a dynamic system evolving over time. Adaptation builds complexity (Holland, 1995). Based on complex adaptive system and considering the features of supply network, more and more valuable managerial insights for the design, maintenance and improvement of supply networks can be obtained from the evolution research.

Current research on supply network evolution has been increasingly becoming the focus of attentions. Various methods have been adopted, including the analytical method (Gumus, Guneri, & Keles, 2009), game theory (Pathak, Dills, & Biswas, 2007), system dynamics (Ozbayrak, Papadopoulou, & Akgun, 2007), simulation (Lin & Long, 2011; Long, Lin, & Sun, 2011), and computational experiment (Long, 2014). Two analytical methods used in supply network evolution are the control theory approach and the operational research approach, both of which rely on mathematical formalizations, and the obtained models necessitate simplifying approximations, usually restrictive, and are limited for taking into account time (Labarthe, Espinasse, Ferrarini, & Montreuil, 2007). Game theory is always used to study the equilibriums of supply networks evolving over the parties' multiple choices. System dynamics is usually

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adopted to study the inherent causalities, which lead to the evolution of supply networks. Simulation and computational experiment emphasize what-if analysis and study the internal mechanisms for supply network evolution by means of the network reproduction. However, the recent studies are insufficient; and further research is required. First, most supply network evolution models are too abstract. They focus on the structural evolution with theoretical parameters (Li & Chan, 2013; Russ & Walz, 2009; Zhang & Liu, 2013), aim to discover the general evolution laws of supply networks (Li, Ji, Sun, & Lee, 2009; Li, Sun, Ji, & Li, 2005; Li, Yang, Sun, Ji, & Feng, 2010), and put little emphasis on the application research of supply network evolution. Therefore, the value of their research results in practical applications is weakened. Second, regardless of information and time flows, the recent research in modeling supply networks only considers the material flow (e.g. the network structure) and conducts the supply network evolution in a centralized virtual environment, which greatly affects the structural evolution of supply networks. Customer demand is usually modeled by a time-dependent sequence of customer orders. Specially, the time flows need to be considered when supply network evolution is conducted in a distributed environment with partial information sharing. All enterprises' time flows need to be collaborated together to ensure that the event causality in the virtual supply networks is consistent with that in the real ones. The time series analysis of evolution results also contains time factors. Time flow makes it possible to do time series analysis of supply chain network evolution. Third, the distinctive features of distributed environment and partial information sharing of supply networks are important factors that cannot be ignored, because they directly determine the selection of research methods and the validity of the research results. Supply network evolution conducted in a distributed environment can gain more actual evolution results than that in a centralized environment, but it calls for an efficient research method which can support distributed computation. Partial information sharing results in different evolution path of supply networks from that with complete information sharing. It is absent in the current studies of supply network evolution. These features call for an efficient method that supports distributed computation with partial information sharing for supply network evolution and can lead to more valuable managerial insights for the design, maintenance and improvement of supply networks than that of the centralized computation with complete information sharing. Finally, the current research methodologies need to be further improved to fit the new research needs of supply network evolution.

Considering the above issues and taking advantage of a new methodology—agent-based computational experiment (Long, 2014), this paper inherits the related research to supply network evolution, explores the key issues in agent-based computational experiment for complex supply network evolution, and proposes a three-dimensional-flow model integrated with material, information, and time flows as well as its formal description. In this model, the approaches for static structure modeling and dynamic evolution modeling are given to elaborate the material flow modeling. In information flow modeling, a general approach for order hierarchical decomposition based on product process is proposed. This paper also provides a solution for inter-organizational and intra-organizational agent coordination based on public and private ontology with partial information sharing. With this solution, the issue of consistent knowledge understanding for agent interaction driven by information flow in a distributed and heterogeneous virtual environment is solved. Supply network evolves along with time flow. To support time flow collaboration among agents in a distributed and heterogeneous virtual environment, a time flow collaboration scheme based on decoupled model and asynchronous parallel is proposed when the supply network structure is taken into consideration. This scheme maximizes the efficiency of agent collaboration, meanwhile, the correct event causality in a virtual computational experiment environment is ensured. Finally, to support implementing the proposed three-dimensional-flow model, a reference architecture integrated three-dimensional flows into agent-based computational experiment for supply network evolution is given, and the implementation solutions of its multiple layers are also explored. A supply network case is simulated using the proposed three-dimensional-flow model and the reference architecture. The simulation results demonstrate that the three-dimensional-flow model is efficient. The reference architecture is effective in the three-dimensional-flow model implementation. The evolution data obtained from computational experiments can support time series analysis for supply network design, maintenance and improvement. The contributions of this paper are that: (i) the recent research referring to the structural evolution of supply networks is improved; (ii) the current evolution models are extended; (iii) information and time flow models are introduced into agent-based computational experiments in a distributed and heterogeneous virtual environment. As a result, the value of the research findings in practical applications is strengthened. This paper also provides a valuable reference about how to implement the three-dimensional-flow model into agent-based computation experiment.

The rest of this paper is organized as follows. Section 2 presents a series of related studies. Section 3 explores the key issues in agent-based computational experiment for complex supply network evolution. Section 4 describes the three-dimensional-flow model for supply network evolution and its modeling approach in details. Section 5 gives a reference architecture integrated three-dimensional flows into agent-based computational experiment for supply network evolution. Section 6 shows a supply network case. Section 7 concludes the paper and presents the directions for future research.

## 2. Related work

It is a new hotspot to conduct the research on the evolution of supply networks instead of the optimization of supply chains. There is a volume of literature related to supply network evolution. Most of it focuses on the structure dynamics of supply networks using agent and simulation technologies based on complex adaptive system (Lin & Long, 2011; Long et al., 2011; Long, 2014). Agent can adaptively perceive the environment, interact with other agents, and make self-decisions. Supply network is always modeled as a multi-agent system (Chatfield, Hayya, & Harrison, 2007; Jiang, Hu, & Wang, 2010; Lees, Logan, & Theodoropoulos, 2007) from the microscopic perspective. Simulation is a scientific research method that a model instead of the real complex system is built and simulated to study the real system (Jiang & Lin, 2004). It is a mainstream methodology for studying supply network evolution to simulate a microscopic multi-agent system to obtain a macroscopic emergence of the network.

Based on complex adaptive system and fitness landscape theory, Li et al. (2010), Li et al. (2009, Li et al. (2005) first proposed an evolution model of complex adaptive supply networks in order to understand the general principle of the network evolution. A multi-agent simulation, conducted on the evolution model, disclosed that the external environment factors and firm-internal mechanisms appear to be the dominant forces that shape the gradual evolution of complex adaptive supply networks and the evolution is highly sensitive to the initial condition, and is path dependent and difficult to predict precisely. Similarly, Adamides and Pomonis (2009) adopted the necessary evolutionary economics perspective to investigate how manufacturing strategy emerges as a result of a coordinated search in the three correlated fitness