Expert Systems with Applications 41 (2014) 4094–4112

Contents lists available at ScienceDirect

Expert Systems with Applications

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

An agent-based distributed computational experiment framework for virtual supply chain network development

Qingqi Long *

School of Information, Zhejiang University of Finance & Economics, Hangzhou, Zhejiang 310018, China

ARTICLE INFO

Keywords:
Agent
Computational experiment
Virtual supply chain network

ABSTRACT

This paper focuses on research on virtual supply chain networks instead of real supply chain networks by making use of agent technology and computational experiment method. However, the recent research is inefficient in computational experiment modeling and lack of a related methodological framework. This paper proposes an agent-based distributed computational experiment framework with in-depth study of material flow, information flow and time flow modeling in supply chain networks. In this framework, a matrix-based formal representation method for material flow, a task-centered representation method for information flow and an agent-based time synchronization mechanism for time flow are proposed to aid building a high quality computational experiment model for a multi-layer supply chain network. In order to conduct the model, a computational experiment architecture for virtual supply chain networks is proposed. In this architecture, coordination mechanisms among agents based on material flow, information flow and time flow as well as consistency check methods for computational experiment models are discussed. Finally, an implementation architecture of the framework is given and a case of virtual supply chain network is developed to illustrate the application of the framework. The computational experiment results of the case show that the proposed framework, not only feasible but correct, has sound advantages in virtual supply chain network development, computational experiment modeling and implementation.

1. Introduction

A supply chain, consisting of suppliers, manufacturers, distributors, retailers and customers, is a value-added chain that provide to customers products with the quickest delivery and the most competitive price. By expanding its traditional concept, a supply chain is no longer a single chain but a network intertwined with a few chains, called supply chain network (Fasli & Kovalchuk, 2011; Lin & Wang, 2011; Mizgier, Wagner, & Holyst, 2012; Xu, Liu, & Wang, 2008). Thus, the traditional linear supply chain is transformed into a supply chain network (Lu & Wang, 2008). In the network, all the participants play different roles and their relationships are more complicated. These complex supply chain networks are quite common in manufacturing and service industries. Therefore, it is reasonably believed that the study of supply chain networks has more practical value than the study of the traditional supply chains.

Supply chain network studies are always conducted in two types of experiments: experiment on the real network and experiment on a model of the network. In the former type, all studies and experiments are carried out on the real supply chain network; while in the latter type, a virtual supply chain network is used to take the place of the real one. The experiment on the real network is confined by such factors as limits and costs and disruptions on the real network. All these call for research on virtual supply chain networks. Moreover, supply chain network is mostly organized on the basis of virtual alliance, so virtual supply chain network not only better reflects its virtual feature, but also can quickly respond to changes in the real network.

In order to analyze virtual supply chain networks, simulation, especially discrete event simulation (Zengin, 2011; Zengin, Sarjoughian, & Ekiz, 2013), has been widely used in supply chain evaluation as a decision-making tool for supply chain network optimization. However, the previous simulation research did not take into account the characteristics of geographically heterogeneous distribution, partial information sharing, and autonomous decision-making of participants in supply chain networks. The participants in supply chain networks have similar characteristics with agents in structure and function. Both of them have certain resources, can perceive the environment, interact with other participants or agents and make self-decisions. Thus, a supply chain network is always modeled as a multi-agent system (Chatfield, Hayya, & Harrison, 2007; Jiang, Hu, & Wang, 2010; Lees, Logan, & Theodoropoulos, 2007), because there is a natural correspondence between supply chain participants and agents in a simulation

* Tel.: +86 15168218918.
E-mail address: longqingqi1116@163.com

0957-4174/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.eswa.2014.01.001

model. Combined with agent technology and simulation, agent-based simulations (Amini, Wakolbinger, Racer, & Nejad, 2012) for virtual supply chain networks have arisen as an active research topic. It is now becoming popular to model supply chain networks as multi-agent systems and use discrete event simulation to learn more about their behaviors or investigate the implications of alternative configurations (Tan, Chai, & Liu, 2011).

However, the real system, seen as a benchmark in simulation, is used as the most important criterion for evaluating the validity in simulation modeling, implementation and analysis. If simulation models and results are fully consistent with the real system, the value of simulation is optimistic. If not, the simulation models are gradually being corrected to reduce distortion (Sheng & Zhang, 2011). Different from simulation, the main idea of computational experiment is that computers are used as virtual labs of complex systems and system behaviors are analyzed by a large number of experiments. This idea is a natural extension of computer simulation, but it has a fundamentally different meaning from simulation. Although generally speaking, computational experiment is also treated as a kind of simulation, the "reality" in computational experiment is no longer viewed as only "a" situation or "an" orbit or "a" path in the real system but as "a kind of" several possible situations or orbits or paths due to path dependence, irreversibility, uncertainty and bifurcation of the evolution trends (Sheng & Zhang, 2011). Therefore, computational experiment tries to reproduce a bunch of social realities with computers.

Agent-based computational experiment of supply chain networks has been recognized over the past decade and currently it has become an international hot issue in supply chain network research. However, the recent research is inefficient in computational experiment modeling and lack of a related methodological framework.

Firstly, most of the current research only makes use of the present simulation tools (e.g. Repast, Swarm et al.) to carry out case studies for specific supply chain networks with computational experiment method, so that a generic agent-based computational experiment framework for complex supply chain networks has not been systematically built yet. This generic framework is beneficial to model a wide range of supply chain networks with high quality and guide the related computational experiment systems development.

Secondly, the few existing frameworks are designed only for agent-based modeling and simulation and provide only basic specifications from a conceptual point of view. Although these basic specifications provide large space and freedom for modelers to build their required agent-based simulation models, they increase the difficulties in model development. Therefore, an operational framework considering freedom and easiness in modeling process is valuable for modelers to build their required models in a building block way.

Thirdly, agent-based computational experiments of supply chain networks are almost carried out in a centralized way. In this way, the characteristics of geographically heterogeneous distribution and partial information sharing in supply chain networks are not taken into account. Therefore, their value for the design, evaluation and optimization is discounted.

Fourthly, there is no time flow concept in centralized simulations or computational experiments. In order to support distributed computational experiments, time flow and a related time synchronization mechanism should be taken into account. It presents a new challenge for agent-based distributed computational experiments.

Moreover, the recent research only proposes conceptual frameworks. The solutions to implement these frameworks are not involved. Therefore, an implementation architecture needs to be studied and a case study needs to be conducted to verify the proposed framework.

Taking into account the above issues, this paper focuses on an efficient and operational solution for supply chain network computational experiments. The aim of this paper is to propose an agent-based distributed computational experiment framework for virtual supply chain networks, including an approach for agent-based computational experiment modeling based on material flow, information flow and time flow, and a computational experiment architecture as well as its implementation architecture for model implementation in a distributed environment.

This framework is quite innovative for the fact that it is a generic computational experiment methodology covering model building to model implementation in supply chain network research. This generic framework provides a reference model for modeling a wide range of supply chain networks with high quality and guiding the related computational experiment systems development. In this framework, an operational computational experiment modeling approach based on material flow, information flow and time flow is proposed. This approach provides modelers with several types of agents to build their computational experiment models rapidly by using these agents as building blocks. With this approach, the modeling difficulties are reduced while the model reusability is improved. Moreover, to implement the framework in a distributed environment, a computational experiment architecture is proposed, in which the characteristics of geographically heterogeneous distribution and partial information sharing of supply chain networks are perfectly simulated. In this architecture, coordination mechanisms among agents and consistency check methods for computational experiment models are proposed. Finally, an implementation architecture is given and a case of virtual supply chain network is developed to verify the proposed framework.

The rest of this paper is organized as follows: Section 2 is related work; Section 3 discusses the agent-based virtual supply chain network; Section 4 proposes an agent-based distributed computational experiment framework for virtual supply chain network development; Section 5 proposes a virtual supply chain network modeling approach; Section 6 proposes a computational experiment architecture for virtual supply chain networks; Section 7 presents an implementation architecture; Section 8 implements the proposed framework with a case study; Section 9 is conclusions.

2. Related work

2.1. Multi-agent systems in supply chain network research

A supply chain network is always considered as a complex inputs–outputs network system, in which input elements will be transformed into output elements via the function of network structure. In order to model the complex topological structure of supply chain network, Lu and Wang (2008) expanded the typical N inputs–outputs network system (Xue & Feng, 2005) as the M-layer N input–output channels network system and treated the network system as an equivalent topological structural network economy system to simplify the problem and accentuate the main characteristics. In addition to its structure, the participants in supply chain networks have similar characteristics with agents in structure and function. Both of them have certain resources, can perceive the environment, interact with other participants or agents and make self-decisions. Thus, a supply chain network is always modeled as a multi-agent system (Chatfield et al., 2007; Jiang et al., 2010; Lees et al., 2007), which considers: (i) the characteristics of distribution, heterogeneity and nonlinear of supply chain network; (ii) the flexibility and convenience in changing scenarios; (iii) the complexity and diversity