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A multi-methodological collaborative simulation for inter-organizational supply chain networks

Qingqi Long*

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

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ABSTRACT

Inter-organizational collaborative simulation requires covering the knowledge of agent, flow and process to qualifiedly represent the supply chain network operation. This paper proposes a multi-methodological collaborative simulation framework for inter-organizational supply chain networks. This framework integrates the agent-based, flow-centric and process-oriented methodologies. This framework establishes a collaborative knowledge representation approach for simulation modeling. In the approach, a multi-agent system is adopted to represent the inter-organizational structure of a supply chain network; the three flows of material, information and time are enabled to represent the operational mechanisms; and the processes are used to represent the micro behaviors of agents. This approach integrates the knowledge of agent and process with that of flow and solves the problems regarding the integration of the agent-based, flow-centric and process-oriented methodologies. To implement the inter-organizational collaborative simulation, a collaborative framework is proposed. This framework integrates multiple simulation formalisms, such as time series increments, event scheduling, policy control, process interaction and activity scanning; it promotes the unification of the three different methodologies. A case of a five-level manufacturing supply chain network is studied using the proposed framework. The findings indicate that the proposed framework is particularly qualified in the knowledge representation of a supply chain network and is effective in implementing the inter-organizational collaborative simulation in a decentralized manner; in addition, it is well contributive to collaborative decision making through KPI analysis.

1. Introduction

A supply chain network is a complex adaptive system composed of several enterprises with a certain structure. The network is an integrated process wherein raw materials are manufactured into final products, then delivered to customers [3]; it is no longer a single chain but a network intertwined with a few chains [9,18,26,40]. Competition and cooperation coexist among enterprises in the network. The networks should cross their boundaries to implement inter-organizational collaboration through such activities as planning, production, inventory and delivery to strengthen the competitiveness of the network [6]. The inter-organizational supply chain network has the following characteristics: dynamic reconfigurable structure, complex collaborative processes and adaptive collaborative decision making. These characteristics are doomed to pose challenges to both its theoretical research and applications. Particularly, it is a great challenge to connect decision making activities of enterprises into a unified systematic framework.

Simulation is an effective methodology for complex systems; it supports the emergence analysis from micro activities to macro phenomena. In addition to such methodologies as operational research and control theory [43], it is another effective tool for quantitative research on the supply chain network. In view of the inter-organizational characteristics, enterprises in decentralized environments should be included in a unified collaborative simulation framework. Inter-organizational collaborative simulation is a framework that models the structure of a supply chain network and its micro inter-organizational operational mechanisms. This collaboration establishes the relation between the enterprises' micro activities and the macro network phenomena and supports the what-if analysis for the design and optimization of a supply chain network by means of a variety of virtual reproductions.

Inter-organizational collaborative simulation solves difficulties in modeling the complex collaborative processes and matching between macro phenomena and micro activities. An increasing volume of literature concerns inter-organizational collaborative simulation for supply chain networks. This literature generally adopts two methodologies: process-oriented simulation methodology and agent-based simulation methodology. A process-oriented

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

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simulation uses processes as the basic modeling units and simulates the process sequence (process flow) in a centralized manner, for example, the studies of Jakkhupan et al. [13], Longo and Mirabelli [24], Windisch et al. [37], Mohammadi et al. [27], and Windisch et al. [38]. These studies exploit the intrinsic attribute, a process, in a supply chain network operation, aiming to represent the entire operation by means of micro processes. However, these studies are weak in supporting the representation of the enterprises' decision making capabilities, partial information sharing context and geographical decentralized environment. This weakness results in a discount of the simulation fidelity and effectiveness. A multi-agent system promotes the studies on collaborative simulation for supply chain networks. In contrast to the process-oriented methodology, agent-based simulation utilizes a complex system research perspective. On the one hand, it uses an agent as the basic modeling unit to represent the micro entities and their interactions; on the other hand, it uses a multi-agent system to simulate the supply chain network operation for the emergence of macro phenomena. A large volume of literature focuses on this topic, for example, the studies of Santa-Eulalia et al. [32], Labarthe et al. [15], Bahroun et al. [2], Li et al. [16], and Long et al. [22]. Considering the agent attributes of enterprises, these studies take advantage of distributed computing capability of multi-agent system to describe geographical distribution and support collaborative simulation under the context of partial information sharing. These are consistent with real supply chain network, with higher credibility and utility in the conclusions. However, agent-based simulation has several shortcomings. It is weak in representing the information flow [5], material flow and time flow [19,21]. The combination of process-oriented and agent-based methodologies can contribute to an effective solution [5,11,20]. Although this combination has obvious advantages, defects remain. First, there is no framework that is established for inter-organizational collaborative simulation of a supply chain network; in particular, no knowledge representation regarding its inter-organizational collaboration is involved. Second, the knowledge related to the agent and the process in the supply chain network has been described in current studies. However, these studies failed to integrate the knowledge of the agent and process with that of the flow and address the contradiction of the agent-based, flow-centric and process-oriented methodologies in their integration. Third, these studies ignored the abovementioned knowledge in their frameworks to achieve a more realistic, effective and credible simulation to support effective decision making. All of these challenges provide great opportunities and motivations for the research in this paper.

This paper proposes a multi-methodological collaborative simulation framework for inter-organizational supply chain networks. This framework develops a knowledge representation of inter-organizational supply chain network and its formal description for collaborative simulation. In the framework, a multi-agent system is adopted to develop the inter-organizational network structure; the three-dimensional flows represent the operational mechanisms; and the processes instantiate agents' behaviors. Integration of a multi-agent system, the three-dimensional flows and operational processes helps to support the effective emergence of supply chain network. To implement the inter-organizational collaborative simulation, a collaborative framework is proposed. This framework integrates multiple simulation formalisms, such as time series increments, event scheduling, policy control, process interaction and activity scanning; it promotes the unification of the agent-based, flow-centric and process-oriented methodologies. A case of a five-level manufacturing supply chain network is studied using the proposed framework. The findings indicate that the proposed framework is particularly qualified in the knowledge representation of supply chain network and is effective in implementing the inter-organizational collaborative simulation in a decentralized manner; in addition, it is well contributive to collaborative decision making through KPI analysis.

The remaining of this paper is organized as follows: Section 2 presents a series of related work. Section 3 proposes a multi-methodological collaborative simulation framework for inter-organizational supply chain networks. Section 4 puts forth a multi-formalism collaborative framework for simulation implementation. Section 5 conducts a case study to verify the proposed collaborative simulation framework. Section 6 concludes.

2. Related work

According to the different modeling methodologies, simulation for a supply chain network can be divided into two categories: process-oriented simulation and agent-based simulation.

Process-oriented simulation uses micro processes as the basic modeling units; thus, it has obvious advantages in the abstract description of a supply chain network operation in simulation modeling. Tako and Robinson [33] studied the application of discrete event simulation and system dynamics in the logistics processes and in a supply chain context. Jakkhupan et al. [13] studied business process analysis and simulation for the RFID and EPCglobal Network-enabled supply chain. Cannella et al. [4] presented a simulation-based study of a coordinated, decentralized linear supply chain system. Longo and Mirabelli [24] proposed an advanced modeling approach and a simulation model to support supply chain management using a process-based simulation package, the eM-Plant. Karagiannaki et al. [14] proposed a framework for mapping the RFID-enabled supply chain process redesign in a simulation model. Windisch et al. [37] applied a methodological framework to investigate two supply chains in different operational environments to identify the business processes and stakeholders that comprise the supply chains, using a business process mapping methodology. Mohammadi et al. [27] proposed a methodology combining two approaches (i.e., grammar-based business process modeling and simulation) to facilitate process thinking. Reiner [31] described how process improvements can be dynamically evaluated under consideration of customer orientation and supported by an integrated usage of discrete-event simulations models and system dynamics models. Fröhling et al. [10] developed closed-loop supply chain planning systems by elaborating and implementing an operational planning approach for integrated planning of transportation and recycling for multiple plants based on process simulation. Windisch et al. [38] investigated an information-based raw material allocation process for increasing the efficiency of an energy wood supply chain using discrete-event simulation. Groznik and Maslaric [12] conducted a case study to investigate the impact of information sharing in a two-level supply chain using business process modeling and simulations. Wang et al. [36] evaluated the value of collaboration in a supply chain through business process simulation. With the power of business process simulation, the researchers have the capability to evaluate the benefits of collaboration considering the details of the operations and the stochastic characters. Persson [29] developed a simulation tool for a supply chain simulation based on the second version of the SCOR template that contains all major processes.

In contrast to a process-oriented simulation, agent-based simulation uses an agent as the basic unit to model the entities in a supply chain network. This simulation aims at the emergence of macro performance by means of agents' decision making and behaviors as well as their interactions in multi-dimensional flows. This methodology has advantages in observing the macro phenomena of supply chain network that emerges from its micro activities.

Santa-Eulalia et al. [32] presented a novel methodological framework called FAMASS (FORAC Architecture for Modeling Agent-based Simulation for Supply chain planning), which provides