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An integrated framework for agent based inventory–production–transportation modeling and distributed simulation of supply chains

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ABSTRACT

A supply chain is a complex stochastic adaptive system featuring dynamics, uncertainty, and partial information sharing. Though agent-based discrete event simulation is a more efficient method of handling those features than the traditional analytical methods, agent-based modeling and simulation of supply chain requires the integration of a mature modeling and simulation theory, an excellent modeling framework, and a special simulation platform. This paper proposes an integrated framework for agent-based inventory–production–transportation modeling and distributed simulation of supply chains. This paper's multi-level framework comprises four levels—from domain modeling to the implementation of multi-agent systems—and integrates the agent-based modeling and distributed simulation theory, a four-layered conceptual agent modeling framework, a meta-agent class library, and a multi-agent based distributed simulation platform to build an agent-based inventory–production–transportation model and simulate it in a distributed way. It extends the conceptual modeling framework. This extended framework provides users with a meta-agent class library and a multi-agent based distributed platform for supply chains with which to build an agent-based simulation model visually and rapidly by using meta-agents as building blocks. Further, it supports the independent building of sub-simulation models, implementing and synchronizing them together in a distributed environment. Therefore, the proposed integrated framework has strong flexibility in multiple layers, multiple granularities, reusability, and scalability in simulation modeling. A three-echelon supply chain is modeled and simulated to illustrate the proposed integrated framework.

1. Introduction

A supply chain can be defined as a network of autonomous or semiautonomous business entities collectively responsible for moving a product or service from supplier to customer [9]. Supply chain management (SCM) is defined as a set of approaches taken to efficiently integrate suppliers, manufacturers, distributors, and retailers in order to deliver products on time to customers at a competitive price [21,30,48]. The two traditional analytical methods used in SCM are the control theory approach, based on differential equations, and the operational research approach, which relies on optimization theories

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and algorithms [14,31–43]. However, a supply chain is a complex adaptive system [24], is stochastic, and features a complex structure, dynamics, uncertainty, and partial information sharing. Traditional analytical methods are thus ineffective in supply chain modeling and model resolving. Such methods rely on mathematical formalizations of the supply chain and thus necessitate simplified approximations, are usually restrictive, and are limited in their consideration of time [14]. Therefore, the analytical methods significantly reduce the value of research that employs them.

To overcome the shortcomings of the analytical methods, simulation has been widely used in supply chain evaluations as a decision-making tool for supply chain optimization. Supply chain modeling and simulation was originally based on system dynamics [10,14,47] because the performance of a supply chain is determined by its structure and flow control. Supply chain modeling and simulation was later assessed through continuous simulation and discrete event simulation [15]. Discrete event simulation [45,46], with its strong, realistic modeling and analysis capabilities, is the preferred mainstream method in supply chain research [44]. Supply chain simulation can be used either for descriptive or normative purposes [14]. The former aims to help decision makers better understand the behavior and performance of the modeled supply chain, and offer managerial guidance. The latter uses simulation to improve the function and performance of the supply chain by identifying the best decisions to take regarding structural, organizational, managerial, and process transformations. However, previous simulation studies have not taken into account the geographically heterogeneous distribution, partial information sharing, and autonomous decision-making of enterprises in a supply chain. Multi-agent technology [4,5,27], from the field of artificial intelligence, furnishes the best mechanism for modeling the supply chain's autonomy, communication, coordination, and decision making. Interest has recently grown in modeling supply chains as agent-based systems [7,16], as there is a natural correspondence between supply chain participants and agents in a simulation model. In addition, supply chains tend to be decentralized systems, with participants acting independently, according to their own interests and policies. Agent-based modeling and simulation significantly extend the capabilities of discrete event simulation for both descriptive and normative purposes in the context of complex knowledge-intensive supply chains [14]. Thus, an agent-based approach to supply chain simulation has several advantages [7]. Therefore, multi-agent technology can be used to implement a distributed supply chain simulation.

Agent-based modeling and simulation of supply chain has witnessed a boom over the past decade and has become internationally significant issues in supply chain research. Such research focuses on agent-based simulation modeling (including case studies) and agent-based simulation platform development. However, these studies are insufficient; and further research is required. First, most research consists of case studies on specific supply chains using existing simulation platforms, ignoring the comprehensive frameworks or methodologies for agent-based supply chain modeling and simulation. Second, the few extant studies on agent-based modeling and simulation frameworks or methodologies provide only basic specifications from a conceptual point of view. Although these basic specifications allow modelers a great deal of freedom in the building of their required agent-based simulation models, they also increase the difficulties of model development. Third, agent-based supply chain simulations are highly centralized and, therefore, fail to evaluate the characteristics of geographically heterogeneous distribution and partial information sharing in supply chains; the value of the design, evaluation, and optimization of the supply chain is, therefore, discounted. Fourth, the agent-based simulation platforms developed by research institutions and universities (like Swarm and Repast) are generic systems that are not designed solely for supply chains, making it difficult to use them to develop supply chain simulation models. Finally, agent-based supply chain modeling and distributed simulation should help users develop and implement simulation models with multiple layers, multiple granularities, reusability, and scalability.

This study addresses the above issues in the integrated framework for agent-based inventory–production–transportation modeling and distributed simulation of supply chain it proposes. This framework uses multiple levels and steps to provide the specifications for agent-based modeling and distributed simulation of supply chain through agent-based modeling and simulation theory and technology. It integrates the agent-based modeling and distributed simulation theory, a conceptual modeling framework, a meta-agent class library, and a multi-agent based distributed simulation platform to build an agent-based inventory–production–transportation model and simulate it in a distributed way. Inheriting ideas from a previous conceptual modeling framework, the proposed framework makes an important contribution by extending the conceptual modeling framework. This extended framework provides users with a meta-agent class library and multi-agent-based distributed supply chain platform upon which to visually and rapidly build an agent-based simulation model by using meta-agents as building blocks. Further, it supports the independent building of sub-simulation models, implementing and synchronizing them in a distributed environment. Therefore, the proposed integrated framework has strong flexibility in multiple layers, multiple granularities, reusability, and scalability in simulation modeling.

The rest of this paper is organized as follows. Section 2 presents a series of related studies. Section 3 proposes an integrated framework for agent-based inventory–production–transportation modeling and the distributed simulation of supply chain. Section 4 implements the proposed framework in a case study. Section 5 concludes the paper.

2. Related work

2.1. Agent-based modeling and simulation of supply chain

Supply chain simulation is a scientific method by which users employ a model to observe the operation of an entire supply chain and conduct "what-if" analyses for multiple scenarios. There are several kinds of supply chain simulation methods,

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