Agent-Based Modeling and Simulation for Supply Chain Risk Management – A Survey of the State-of-the-Art

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Abstract—Due to the complex nature and numerous interacting factors that contributes to the increased vulnerability of supply chains, traditional methods have been found to be inadequate for Supply Chain Risk Management (SCRM). Agent-Based Modeling and Simulation (ABMS), an agent-oriented approach to model and simulate complex adaptive systems, represents a recent development in supply chain planning that has been regarded highly appropriate for studying risk management [1-4]. The objective of this paper is to provide a multi-perspective survey of the state-of-the-art agent based modeling and simulation approaches for SCRM.

Keywords—supply chain risk management; agent-based modeling and simulation; survey; supply chain risk management process; planning decision level; supply chain design goals

I. INTRODUCTION

Supply chain can be defined as a network of organizations that coordinate and collaborate in a process to obtain resources and materials, converting them into services and products, and distribute the end products to retailers and customers [5]. According to [6], supply chain management (SCM) refers to “the management of material, information and financial flows through a network or organization (i.e., suppliers, manufacturers, logistics providers, wholesalers/distributors, retailers) that aims to produce and deliver products or services for the consumer. It includes the coordination and collaboration of processes and activities across different functions such as marketing, sales, production, product design, procurement, logistics, finance, and information technology within the network of organizations”. As concluded in [7], the biggest portion of the operating expenses incurred by most companies are associated with SCM costs, which can be “as high as 75% of overall operating expenses”. This is even more evident in today’s volatile business environment with ever increasing complexity, in which companies constantly face greater needs for supply chain risk management (SCRM) due to factors such as the globalization of supply chains, increased outsourcing, increased volatility and variability of demand and supply, shortening of product life cycles, etc. In fact, any disruption in today’s supply chain such as natural disaster, strike, and etc., can seriously impact all business entities in the supply chain. For example, the 2011 Tohoku earthquake and tsunami in Japan affected automotive supply networks across the globe. And the fragility of lean supply chain is again exposed by the massive flood in Thailand in 2012 for which “economic losses were estimated by the World Bank at THB1.4 trillion (USD45.7bn)” [8].

According to [6], SCRM can be defined as “the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity”. The aim of SCRM is to create responsive and autonomous but collaborative groups of companies, which work together to reduce overall costs and increase their service level. The design goals include higher robustness and flexibility to meet the stochastic demands of customer and supplier production capacity, while minimizing costs in the events of disruptions. The risks in SCRM usually originate from uncertainty and volatility of the business environment, as well as disruptive events such as natural disasters. Traditional methods in SCRM for dealing with sources of risks such as uncertainty are based on a mixture of mathematical modeling with simulation techniques such as DOE and Monte Carlo simulation [9]. One promising approach is stochastic programming which models uncertainty in mathematical programming. On the other hand, despite their potential, the real-world sizes of mathematical models may still be difficult to solve efficiently using stochastic programming, and its success remains to be seen for solving real-size supply chain risk management problem [9]. However, due to the temporal and spatially distributed nature of supply chains, as well as the stochastic characteristics of their growth over the time, the complexities of many real-world supply chains have escalated to critical levels where traditional methods often fall short. Hence many are also turning to the combination of ad-hoc methodologies and tools as means to tackle the uncertainties and disruptive events of today’s highly complex supply chain [10, 11].
To this end, agent-based modeling and simulation (ABMS or ABM) is today recognized as among the most promising paradigms for detailed investigations and reliable problem-solving of complex real-world supply chains. They assess, evaluate, and respond to supply chain risks by exploring possibilities, diagnosing problems, and finding flexible yet robust optimal solutions in SCM [12]. This is due to their abilities to recreate (with high fidelity level) the intrinsic complexity of real-world supply nets such as the heterogeneous planning domains of diverse supply chain partners and their complex interaction schemas; allow the discovery and assessment of alternative risk mitigation solutions under several constraints; and observe multiple performance measures at the same time. In this survey paper, the use of agent-based modeling and simulation as the enabling technology for SCRM is reviewed from multiple perspectives, with specific focus placed on highlighting the contributions of the approach in the field.

From our survey, it is noted there has been comparatively smaller number of studies that focused on ABMS for SCRM. Our objective in this paper is thus to summarize the state-of-art ABMS for supply chain risk management reported in the literature. In particular, we conduct a classification of these works based on the three viewpoints, namely supply chain risk management processes, supply chain planning decision levels, and supply chain design goals. It is worth noting that such a classification would be informative to both the ABMS and SCRM communities since the number of such efforts remained scarce. Based on the multiple viewpoints, we were then able to conduct a systematic study on existing ABMS for SCRM. Last but not least, we hope that the survey presented here will help promote greater research in ABMS and SCRM and assist in identifying new fruitful research directions.

The rest of this paper is structured as follows. Section II presents an overview on ABMS as well as how it can benefit SCRM. Section III to IV discuss the various ABMS works related to SCRM from three different perspectives: namely supply chain risk management processes, supply chain planning decision levels, and supply chain design goals. Section VI concludes with some suggestions for future research.

II. AGENT-BASED MODELING AND SIMULATION

Originated from the study of complex system and cellular automata, ABMS is an approach to model systems of interacting agents self-governed by their internal rules [13]. In its basic form, ABMS merges discrete event simulation (which provides simulation framework that models the interactions of system components) with object-oriented programming (which provides structure frameworks that arrange and manage agents based on their behaviors). Furthermore, the use of intelligent agent within ABMS enables them to capture the intelligence of the system being modeled [14][15]. To date, there has not been an established definition of the ABMS. For example, [16] defined the ABMS as “a simulation system comprising agents, objects, or entities that behave in an autonomous way”. In other words, agents in ABMS are basically simple software entities capable of sensing their own local environments and executing the assigned tasks in a self-directed manner. These agents can communicate with one another, adjust their behaviors and follow their own agenda to achieve their goals. Each agent makes its individual judgment based on its observations, knowledge, as well as its interactions with other agents and the external environment. The multiplicity of relatively simple interaction among agents, ultimately gives rise to integrative levels and emergence of higher-order intelligence.

ABMS is often used to model supply chains since both can be considered as networks of distributed and collaborative entities whose objectives are to solve problems together. ABMS views the supply chain as composing of a set of enterprise agents, interconnected by physical flow, information flow, financial flow, and etc., with each agent responsible for one or more activities in the supply chain and each coordinating and cooperating with other agents in the planning and execution of their responsibilities [17]. From the perspective of SCRM, the autonomous, social and adaptive behaviors of agents in ABMS improve the adaptability of the supply network, reduce variability and costs associated with management, as well as remove some barriers to widespread collaboration among supply network patterns.

Compared to traditional mathematical programming approach in solving SCRM problems, ABMS offers several advantages [18]. First of all, no mathematical sophistication is needed; object-oriented and distributed nature of ABMS facilitates modeling the intrinsic complexity of a supply chain without involvement of sophisticated mathematical models, since enterprises in a supply chain (e.g. manufacturer, wholesaler, etc.) have a natural translation to agents. Secondly, supply chain risk sources such as disruptive events and uncertainties can be naturally modeled in agents’ behaviors since they are able to incorporate discrete-event simulation mechanisms. Finally, these systems provide a very comprehensive simulation and analysis environment for comparing alternative risk mitigation solutions in supply-chain setup with various constraints based on multiple performance measures (e.g. in SCRM, these responses may be the fill rate or service percentage, etc.). ABMS also can be hybridized with methods such as DOE (which treats simulation as black box) in that they are able to model events such as order, shipment, machine breakdowns, and etc., in great details [19].

In this survey, the application of ABMS to SCRM is investigated from the following perspectives:

- Supply Chains Risk Management Processes:
  - Risk Identification
  - Risk Assessment
  - Risk Response
• Risk Monitoring and Evaluation

- Supply Chain Planning Decision Levels:
  - Strategic Planning
  - Tactical Planning
  - Operational Planning

- Supply Chain Design Goals:
  - Robustness towards Uncertainty
  - Flexibility towards Disruption

These perspectives categorize ABMS works in SCRM from different aspects and are not mutually exclusive. For example, risk response in supply chain risk management processes can be either implemented in the tactical or operational planning decision levels, and may be developed to achieve a robust supply chain design or a flexible supply chain design.

III. SUPPLY CHAIN RISK MANAGEMENT PROCESSES

In supply chains, typical risk management processes include: risk identification, risk assessment, risk response, and risk monitoring & evaluation [20]. Most research works on ABMS in SCRM can be aligned with one or more of these processes. In this section, we present ABMS works in SCRM according to the risk management processes they are involved in.

A. Risk Identification and Risk Assessment

While most of ABMS can be used for risk identification, there are relatively few works in ABMS that have been dedicated exclusively to risk identification. One example is [21] which models a supply chain network under supplier risks. To identify supplier risks, unexpected events randomly arrive in the supply chain to imitate the source of risks that possibly occur in the supply chain, which can be tuned via duration and frequency [21].

There have also been some ABMS studies on risk assessment. For example, [22] developed simulation models based on several networks to evaluate stochastic demand and supply disruptions, and concluded that the two sources of risks effect very different impacts on optimal supply chain design. On the other hand, a simulation model was constructed in [23] for a large consumer products company to assess their vulnerability to disruption risk and quantify its impacts on customer service by capturing risk profile for the supply chain locations and connections using Monte Carlo simulation and modeling the flow of material and network interactions via discrete-event simulation. As another example, [24] described a simulation-based inventory management tool developed for the IBM Enterprise Server Group. To model the impact of randomness on lead times, yields and component usage rates, the authors developed an ABMS tool that took inventory costs and Days-of-Supply profiles as the outcomes in consideration. [25] also proposed an agent-based modeling framework that provides the ability to model supply, demand, and process uncertainty within the supply chain as well as to perform a detailed risk analysis, which is used to measure performance of alternative policies through simulation under different assumptions about uncertainties.

B. Risk Response

Risk response refers to mitigation strategies in the supply chain that minimizes the cost associated with the risk as well as customer service disturbances in the event of disruption. Various mitigation strategies have been studied and evaluated in ABMS for SCRM. For example, [26] proposed an ABMS model that uses the transshipment policy for multi-location inventory system with several retailers who share a common supplier. The model employs a decentralized transshipment strategy which led to emergent transshipments happening between retailers when inventory position does not meet the demand. On the other hand, [27] studied the influence of lead time and information sharing among the four agent types (namely, retailer, wholesaler, distributor, and manufacturer), using a 4-level multi agent-based system model for supply chain inventory with a decision-making model for every enterprise agent in the supply chain. Results confirmed that information sharing strategy effectively decreases the variation amplitudes of inventory of each enterprise in the supply chain. That is, the bullwhip effect is diminished when enterprises in the supply chain share information. In another work, [21] used an agent based simulation model to determine appropriate risk mitigation strategies for a supply chain network under supplier risks. They considered two risk mitigation strategies, i.e., having a redundant supplier and reserving more inventories, were applied and compared for 4 different types of risks based on frequency and duration. Using average total operating cost and average product shortage as performance measures, results are generated for appropriate strategy corresponding to each type of risk. Other examples can be found in [23] which modeled various strategies for coping with risk associated with disruptive event and uncertainty in the system in order to maintain product availability to the customer. The simulation model allows them to effectively assess the various customer behaviors while evaluating the trade-off between service level and inventory investment. [23] further discussed the dynamic nature of risk in the network and the importance of proactive planning to mitigate and recover from disruption.

C. Risk Monitoring and Evaluation

On risk monitoring and evaluation, the use of ABMS tools supports the evaluation based on multiple performance measures, and under the heterogeneous supply-chain setups that combine multiple constraints and critical parameters such as inventory control policies, lead times, demand variability, etc [28]. It has been highlighted in several ABMS approaches for SCRM [10] that successful results should be based on measuring multiple performance indices. Complete analysis of the recent qualitative performance measures, including supply chain resilience and vulnerability, are reported in [29, 30].

IV. SUPPLY CHAIN PLANNING DECISION LEVELS

In SCRM, supply chain planning basically covers three decision levels: strategic planning, tactical planning and operational planning [31]. In this section, we study the ABMS
in terms of the planning decision levels they focus on in SCRM.

A. Strategic Planning

Strategic planning focuses on long-term and high-level decisions in support for the vision and goals of an organization, such as supply chain network design. One example is the beer game, which illustrates the bullwhip effect [32-34]. Other examples include [35] which extended ABMS model with optimization to solve the supply chain configuration problems for new products. As further examples, [36] presented a framework of applying ABMS and simulation-based optimization techniques to supply chain management, which plans how enterprise agents pursue their personal goal(s) as well as how they react and interact with each other for more holistic goal(s). On the other hand, [37] proposed a collaborative inventory management framework in SC using ABMS. [38] addressed the bullwhip effect by developing an ABMS model to minimize overall costs and reduce the bullwhip effect with the use of soft computing techniques. [14] proposed an agent-oriented Petri net model for an inventory scheduling model, which endeavors to investigate the organization structure and dynamic behavior of a system. [39] and [40] provide comprehensive surveys on agent-based modeling in domains of manufacturing which explores problems of uncertainty and temporal dynamics with emphasis on the strategic aspects of decision behavior in the context of manufacturing complex and uncertainty.

B. Tactical Planning

Tactical planning refers to general plans and policies, such as inventory control policies, to support the organization’s strategic plan and serves as planning constraints at the operational level. Many of the mitigation strategies and inventory control implemented in ABMS for SCRM, such as transshipment [26], redundant suppliers, reserving inventories [21], and etc., focus on tactical planning. By adaptively controlling factors on management control, e.g., production and distribution lot sizes, inventory safety stock levels, production levels, inventory levels, and so forth, these policies and plans help organizations reduce cost associated with the risks in the event of disruption, and steer towards the organizations long-term strategic goals. For example, [28] investigated the robustness of different tactical planning and control policies in an agent-based environment and showed how various relevant planning and control tactical policies can be adapted to obtain a robust supply chain under uncertainties related to demand unpredictability, supply instability and manufacturing variability. [35] developed an optimization algorithm in their ABMS to identify the best inventory levels of all sites on the SC. [41] developed an ABMS system to control inventory and minimize total costs for an SC by sharing forecast and information knowledge. [42] proposed a reinforcement learning algorithm combined with case-based reasoning in a multi-agent supply chain system to study the problem of dynamic inventory control for satisfying target service level in supply chain with non-stationary customer demand.

C. Operational Planning

Planning at the operational level refers to real-time decisions made by managers on the daily operations. Operational plans usually cover a shorter time horizon and contain detailed specific actions and tasks, which when executed correctly, fulfill the tactical objectives. In [24], the ABMS tool developed provides decision support at an operational level, with the model capable of forecasting the future inventory performance for selected high-dollar parts in IBM Enterprise Server Manufacturing. On the other hand, [43] developed agent-based modeling and simulation for berth allocation and crane assignment policies in harbor supply chain management. In another example, [44] proposed an agent based model for a warehouse system, in which three subsystems within the warehouse system (namely, agent based communication system, agent based material handling system, and agent based inventory planning and control system) cooperate to address the fluctuation and uncertainty in demands from customers and provide just-in-time delivery of materials.

V. Supply Chain Design Goals

SCRM concerns with how a supply chain can cope with uncertainty in a dynamic world. Therefore, SCRM has two closely related but distinct supply chain design goals: namely supply chain robustness and flexibility. It is important to distinguish between robustness and flexibility. A flexible supply chain can react to disruptive events by adapting its strategies, tactics, and operations. A robust supply chain has fixed strategies and configuration, and can still perform well under uncertainties and dynamics in its environment [19]. From the functional aspect, supply chain flexibility makes supply chain resilient by enabling the supply chain to adapt to environmental changes induced by disruptive events. On the other hand, supply chain robustness protects the supply chain against uncertainty such as stochastic customer demand or supplier production capacity, by deriving robust and optimal solutions which accommodate changes and uncertainties in its environment.

A. Robustness towards Uncertainties and Changes

There have been quite a number of ABMS studies on building a robust supply chain. One proposed approach is to reduce the expected cost as well as cost variance in a supply chain via simulation-based optimization and ABMS. For example, [45] derived a robust solution for supply chain by searching for appropriate values of the factors that management could control and take into consideration the randomness of the environmental factors. [45] attempted to minimize expected cost (as in classic optimization for problem with uncertainties), but also consider cost variance due to environmental disturbances, which is inspired by Taguchi’s approach [46] that divides important factors into controllable and environmental factors.

Another approach used in ABMS to address uncertainty and changes in supply chain is fuzzy technologies. In such ABMS systems, fuzzy agents are equipped with knowledge bases containing fuzzy rules and perform fuzzy inference. Using
fuzzy concepts to take uncertainty into consideration leads to more flexible, agile and robust environment in supply chains that cope with changes naturally and more effectively. [47] discussed application of fuzzy set theory in finding the supplier with the best overall rating among suppliers. [48] presented a fuzzy system model for SC complex problems, which was shown to be superior to the fuzzy linear programming model. On the other hand, [49] reported a fuzzy supplier selection’s model in which all goals, constraints, and parameters are defined as fuzzy variables, which naturally converts the multi-objective problem into a single objective problem. Fuzzy modeling and simulation of a supply chain in an uncertain environment is also suggested by [50] to obtain an acceptable delivery performance at a reasonable total cost for the whole supply chain.

Other approaches for robust supply chain include mitigation strategies such as information sharing. For example, [51] proposed a cooperative planning in which supply chain partners are given incentive and commitment to collaborate and share both their risks and benefits. The uncertainty-driven cooperation is managed through planner systems with local roles that generate plans to make the future and market demand more predictable. Simulation-based optimization has also been fused with ABMS to provide robust solution whose performance does not vary under uncertainties or changes within a supply chain network. For example, [52] proposed genetic algorithms to reveal the uncertainty of manufacturing environments and to evolution of responsive agent decision behaviors towards changes.

B. Flexibility towards Disruption

Many of the mitigation strategies and inventory control discussed in Section IV.B aims at making the supply chain flexible towards disruption, such as transshipment [26], redundant suppliers, reserving inventories [21], and etc. These strategies and policies adaptively adjusts factors of management can control to make the supply chain more responsive to disruptive events, in order to minimize the cost associated with the disruption and recover from these disruptions. Machine learning methods such as reinforcement learning and case-based reasoning [42], can be applied to form dynamic inventory control for satisfying target service level in supply chain, in the event of disruption. Another approach was proposed in [17] which is based on different coordination strategies in a supply-chain setup where unexpected random break downs in the supply chain occur. The ABMS presented in [17] operates in two modes. In the steady-state mode where there are no breakdowns, the operation of the supply chain makes use of demand and supply forecasting. In the disruption mode, the amount of information sharing and collaboration among the supply chain elements are increased, which effectively lowered down inventory when the processing capacity of supply chain partners is diminished due to disruption. Last but not least, [15] proposed a fuzzy agent based modeling in the framework of integrated supply chain management (ISCM) that uses self-configured information agent to handle with changes in the supply chain environment.

VI. CONCLUSION

Taking a multi-facet viewpoint, this paper has presented various Agent-Based Modeling and Simulation researches in the field of SCRM, focusing namely on supply chain risk management processes, planning decision levels, and supply chain design goals. However, despite the development in supply chain-related ABMS and apart from research works surveyed in this paper, there is comparatively smaller volume of papers that have focused directly on ABMS for supply chain risk management. It is hope that the presented survey will help promote greater research in ABMS and SCRM and assist in the identification of fruitful research areas. One promising research direction is to seamlessly integrate various advanced planning systems (i.e., APS) or other intelligent agents that sits on top of the ERP systems with ABMS. In this way, their functionality can be mutually enhanced to form an integrated supply chain management (ISCM) decision support system. Another research direction concerns the fidelity of the ABMS developed for SCRM. For ABMS to be truly helpful in performing what-if analysis of large supply chains, there must exist a wide range of fidelity within a single model to approach risk handling at different levels of decision making and planning. This can be achieved, for example, by means of variable resolution modeling [53].

ACKNOWLEDGMENT

This work is partially supported under the A*Star-TSRP funding, the Singapore Institute of Manufacturing Technology and the Center for Computational Intelligence (C2I) at Nanyang Technological University.

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