DESIGN OF SUPPLY CHAIN TOPOLOGY TO MITIGATE DEMAND AND SUPPLY RISKS

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ABSTRACT

To achieve competitive advantage, companies have been driven to improve their supply chain by outsourcing their non-core business. However, this increases the external risks, such as the demand and supply risks. Companies face challenges in defining effective supply chain topology to mitigate supply chain risks. In this research, we design supply chain network topologies to mitigate the demand and supply risks. Four supply chain network topologies have been designed to represent different supply chain strategies: efficient, responsive, risk-hedging, and agile strategies. An agent-based modeling approach is proposed to evaluate the performance of the supply chain network topologies under different demand and supply risk scenarios. From the results, we can identify the effective supply chain network topology to mitigate the disruption for a particular risk scenario.

1   INTRODUCTION

Companies have made effort to improve their business performance through globalization, outsourcing and lean practices. Globalization increases the complexity of the supply chains and opens up the companies to more risks (Christopher and Lee 2001). Outsourcing helps to reduce supply chain cost through low cost suppliers and economics of scale (Lee 2004), it may bring with a number of risks, such as potential loss of control and creating uncertainty in the fulfillment of orders (Barthelemy 2003). Lean initiatives introduce processes such as the just-in-time practice to increase efficiency by reducing excess inventory in the supply chain. However, these initiatives will only be effective when there is a stable environment (Tang and Tomlin 2008). In the current market, a company is part of the whole supply chain network (SCN) (Mentzer, DeWitt, Keebler, Min, Nix, Smith, and Zacharia 2001). It is difficult for a single company to manage the supply chain risks, especially when the risk can propagate and amplify throughout the whole SCN (Lee, Padmanabhan, and Whang 2004).

These supply chain risks are obstacles for the growth and continuity of the company. The risks can be categorized into external risks and internal risks. The internal risks are associated with the internal functioning of the company, and these can be managed with the company's internal risk management policies. The external risks can be further categorized into demand risk, supply risk and environmental risk (Christopher 2011). Supply risks include uncertainties in the cost and quantities on the supply to the company; while demand risks refer to uncertainties in the demand quantities and demand for different

types of the products. Environmental risk is not considered in this research. Therefore risk management of the SCN is important to the continuous growth and survival of the whole supply chain.

For example, to decrease the cost of managing different suppliers and to maintain a healthy relationship with the supplier, Hewlett-Packard (HP) has a partnership agreement to source the engines for its laser printers only from Canon (Lee 2004). However, there are restrictions on the order lead time: the order quantity needs to be placed 6 months in advance. Thus, HP faces challenge to react to the changes to market demand responsively due to inflexibility in supply. On the other hand, it also faced problems in the demand side. HP sells its printers in the global market to increase revenue (Lee 2004). However, since countries have varying demands in different types of printers, this causes an overstock of printers when the supply does not match the demand correctly.

To reduce negative effects of the demand and supply risks, supply chain needs to be well-designed to manage the uncertainties in business environment (Lee 2004). This paper aims to design SCN topologies to mitigate the demand and supply risks. An agent-based modeling approach is proposed to design and evaluate the SCN topology. With different SCN topologies and risk scenarios, this research investigates the performance of the supply chain and attempts to determine the suitability of the supply chain topology for a particular risk scenario.

The remainder of this paper is organized as follows: Section 2 gives a background on supply chain strategies, agent-based supply chain models and supply chain performance evaluation. Section 3 describes an agent-based approach to model a supply chain with different network topologies. Section 4 analyzes the performance of the supply chains under different demand and supply risk scenarios. Section 5 summarizes and concludes this paper.

2 BACKGROUND

2.1 Supply Chain Strategies

It is a challenge to identify the right strategy for handling a particular supply chain risk scenario. Using the appropriate strategy can either reduce the likelihood of occurrence of a disruption or reduce the negative implication of the disruption (Tang and Tomlin 2008). Some researches have been done on defining suitable strategies for various risk scenarios in order to mitigate the risks and improve the performance of the supply chain.

Lee (2002) proposed an uncertainty framework and classified the supply chain strategies into four main types: efficient, responsive, risk-hedging and agile strategy. The framework selects supply chain strategy based on uncertainties in the demand and supply. An analysis of different supply chain strategies was conducted through a survey to evaluate the uncertainty framework based on profile deviation approach (Sun, Hsu, and Hwang 2009). However, they provide no quantitative evaluation on the effectiveness of the supply chain strategies on handling the demand and supply uncertainties.

An *efficient strategy* focuses on achieving cost efficiency by eliminating redundant operations (Fisher 1997). This can be done by reducing the connections between business entities in order to ensure smooth flow of product across supply chain. By using only a single supplier, the business can negotiate for better deals for the products, such as more discount for larger order quantities. Similarly, each distribution center only serve a single retailer. This help to decrease the operating cost and simplify the SCN structure.

A *responsive strategy* is flexible and responsive to the changing needs of the customer (Fisher 1997). This strategy can be customized to specific requirements of the customer. Using this strategy, the business firms increases the number of distribution centers to distribute the uncertainties of customer demand among the distribution centers.

A *risk-hedging strategy* focuses on sharing the supply risk among the suppliers. This strategy introduces flexibility by having multiple suppliers (St. George, Yoshino, and Knoop 1998). When there is supply disruption on one of the suppliers, the company can still fulfill part of the orders through the remaining suppliers. Hence there is still partial fulfillment of the orders, not a total disruption to its customer.

An *agile strategy* implements flexibility in handling both the demand and supply risks (Christopher 2000). Similar to the risk-hedging strategy, one of the ways of achieving flexibility is by having multiple suppliers in the supply chain. The business can also increase the links between the distribution centers and the retailers to handle the demand risks. However, there is always additional cost involving in maintaining multiple suppliers and additional connections between the distribution centers and the retailer. Hence the business need to determine whether the cost of implementing the strategy outweighs the benefits of mitigating the risks.

Based on the supply chain strategies described in this section, we design supply chain topologies to handle various demand and supply risk scenarios.

2.2 Agent-based Modeling of Supply Chain

A supply chain consists of business entities, such as customers, suppliers and distributors. Agent-based modeling approach has been used to study global supply chains where the complexity, uncertainty and potential of emergent behaviors are highly prevalent. A SCN can be implemented as an agent-based model, where each agent is a business entity within the supply chain and the agents interact with each other within an environment (Gilbert and Bankes 2002). An agent is designed with a set of properties and polices which guides the interaction between the agents and the environment. The links between the agents represents the material, money and information flow. This bottom up approach simulates the underlying processes believed responsible for the global pattern, and allows us to evaluate the mechanism that is most influential in producing emergent patterns. Through the local changes at the micro-level, it can bring about emergent patterns at the macro level.

Since agent-based modeling is such a promising research area, it has been used in various supply chain studies. Li et al. (2009) proposed an evolution model of supply network to understand the evolution of supply chain. They conducted an agent-based simulation on the model, and showed that the supply network emerges and evolves from interaction amongst companies under dynamic environment. Li et al. (2010) expanded on the previous study by analyzing the evolution of supply networks based on complex adaptive system and fitness landscape theory, through the use of agent-based simulations. These model do not analyze the performance of supply chain from the risk management perspective; only the survivability and network structure of the supply chain is considered. Sinha et al. (2011) used agent-based simulation as a platform for effective and efficient management of large supply chains. They identified the optimal supply chain design using heuristic optimization technique such as the particle swarm optimization. However, the structure of the supply chain is fixed and the simulation does not consider any risk scenarios. Sirivunnabood and Kumara (2009) compare two supplier risk mitigation strategies, redundant suppliers and additional inventories, using agent-based simulations. The research is limited to supplier-related risks only, and does not consider the SCN structure at different tiers.

Although a number of agent-based supply chain simulations have been developed, a few of them are designed to evaluate supply chain from the network topology. In addition, these simulations have not considered the performance of supply chain under different demand and supply risk scenarios.

2.3 Supply Chain Performance Evaluation

After designing the SCN topologies, the performance of each topology needs to be evaluated to determine the effectiveness of the strategy to mitigate a particular risk. There are extensive research on supply chain performance measurement, which can be found in (Gunasekaran and Kobu 2007). This section describes two existing performance indices from literature that can be used to evaluate the performance of the agent-based supply chain model.

The performance measurement of the supply chain mainly depends on whether it creates economic value for the stakeholders. Therefore economic *value-added* (VA) of the supply is often used as the index for measuring supply chain and company level performances (Rappaport 1999, Hahn and Kuhn 2012).

The VA for an agent i is shown in Equation 1, where t is the time step representing a day of operation in the supply chain. $R(t)$ is the revenue at time t, and $C(t)$ is the cost of the company at time t. The quantity T is the total number of time steps, or the total operating time period of the supply chain in days. The cost of the company is the summation of the total inventory cost, back order cost and the operational cost. The revenue of the company at time t is the product of the quantity sold and the selling price of the product.

$$VA_i = \int_{t=0}^{T} VA_i(t)dt = \int_{t=0}^{T} (R_i(t) - C_i(t))dt \tag{1}$$

The VA of the supply chain can be calculated as the accumulated sum of all the VA_i of each agent i in the supply chain, shown in Equation 2, given the number of agents in the supply chain is n.

$$VA = \sum_{i=0}^{n} VA_i \tag{2}$$

The *customer service level* (CSL) is also considered as an important performance index as it gives the percentage of the goal achieved by the supply chain (Bowersox, Closs, and Cooper 2002). Low CSL means that customer orders are not satisfied, resulting in loss of sales. Often business needs to pay penalty for the inability to satisfy the order. The net results of low CSL is reduced revenue and increased cost for the whole supply chain.

Order fulfillment rate measures the percentage of orders fulfilled. The on-time delivery rate for an order k is the ratio of the number of products delivered on-time, D_k, to the total quantity ordered Q_k. The percentage of the orders fulfilled at agent i is given by the summation of the on-time delivery rate of all the orders at time t, as shown in Equation 3.

$$OF_i(t) = \frac{1}{K} \sum_{k=1}^{K} \frac{D_k}{Q_k} \tag{3}$$

If there is only 1 order received at agent i and the order is fully fulfilled, $(OF_i = 1)$. $(TO(t))$ is the total orders received at time t by agent i. The CSL for the agent i over the time period T is given in Equation 4.

$$CSL_i = \int_{t=0}^{T} \frac{OF_i(t)}{TO_i(t)} dt \tag{4}$$

The CSL for the whole supply chain is determined by the summation of all the CSL_i for each agent averaged over the total number of agents n, as shown in Equation 5.

$$CSL = \frac{1}{n} \sum_{i=1}^{n} CSL_i \tag{5}$$

The selection of the performance measurement depends on the business policy. There is no single performance measurement that can fit all the needs of different businesses. Therefore two different performance indices are used in the performance evaluation.

3   AGENT-BASED SUPPLY CHAIN MODEL AND TOPOLOGY DESIGN

3.1 Agent-Based Supply Chain Model

The supply chain model studied in this paper is based on a typical distribution supply chain. Each agent in the model represents a business entity within the supply chain. There are in total three different types of agents: (i) supplier, (ii) distribution center, and (iii) retailer. Two types of event are used in the simulation: *order* and *shipment*. The simulation is executed by time-step, where each time step represents a day of
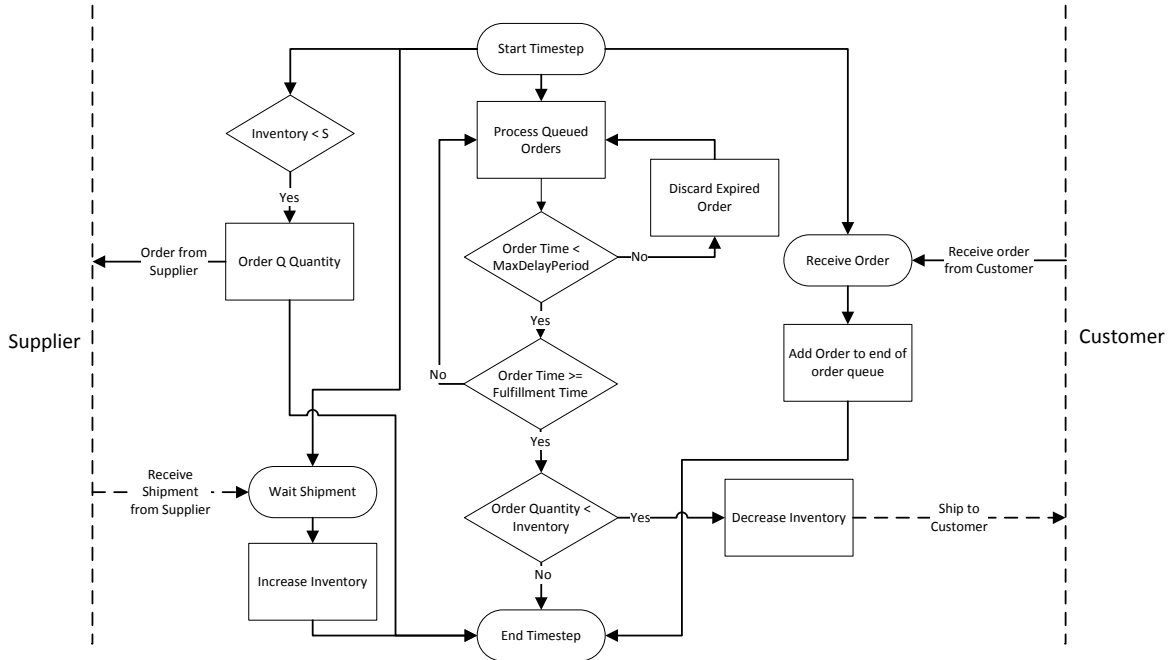
Figure 1: Process flow for a supply chain agent.

operation in the supply chain. At every time step, each agent interacts with each other by exchanging orders and products. Orders are generated to the supplier according to the demand, and the products are delivered by shipment to the customer according to the available supply.

The *order* is defined with an quantity that is requested by the customer (`Order Quantity`) and the time when the order is received (`Order Time`). The amount of product delivered to the customer in a *shipment* is defined as the `Shipment Quantity`.

Every supply chain agent has the same general behavior, which is shown in Figure 1. Each agent is acting both roles of a supplier and customer. At the start of each time step, the agent will process all the pending orders from its customer in the order queue. The orders will be fulfilled based on the *fulfillment time*. When the order time is more than the maximum lead time delay period (`MaxDelayPeriod`), the order is considered as expired and discarded. If the order time has not exceed the fulfillment time, the order will not be processed and remain in the queue. Otherwise, the agent will attempt to fulfill the order if there is sufficient inventory. After reducing the inventory, the ordered quantity is shipped to the customer. At the same time, when the agent receives the shipment from the supplier, the inventory level will be increased according to the shipment quantity received.

The *supplier* introduces products into the supply chain, which will be delivered to other agents. After receiving orders from its customer, the orders are fulfilled according to the defined production policy. The production policy currently is according to *supply rate* of the supply chain, which fulfills orders according to the available supply. A *retailer* agent represents the customer and consumes the products in the supply chain. Orders are generated according to the *demand rate*, which will be fulfilled by its supplier. Both the demand and supply rates are defined as parameters to simulate different risk scenarios in the simulation.

The agents make orders to their supplier based on their internal policies. The internal policy used in the model is the *SQ inventory policy* (Jensen and Bard 2001). The SQ policy is used by all the agents to determine when to replenish their inventory. *S* refers to the reorder level and *Q* is the reorder quantity. When the inventory level drops below the reorder level, the agent will place an order of *Q* quantity to the

supplier. When the agent receives a new order from the customer, it will be appended to the end of the order queue.

In this model, performance indices, VA and CSL, are used to evaluate the performance of the supply chain. At the end of every time step, the performance indices are calculated based on the equations in Section 2.3.

3.2 Supply Chain Network Topology Design

(a) Efficient Strategy (ES)   (b) Responsive Strategy (RS)

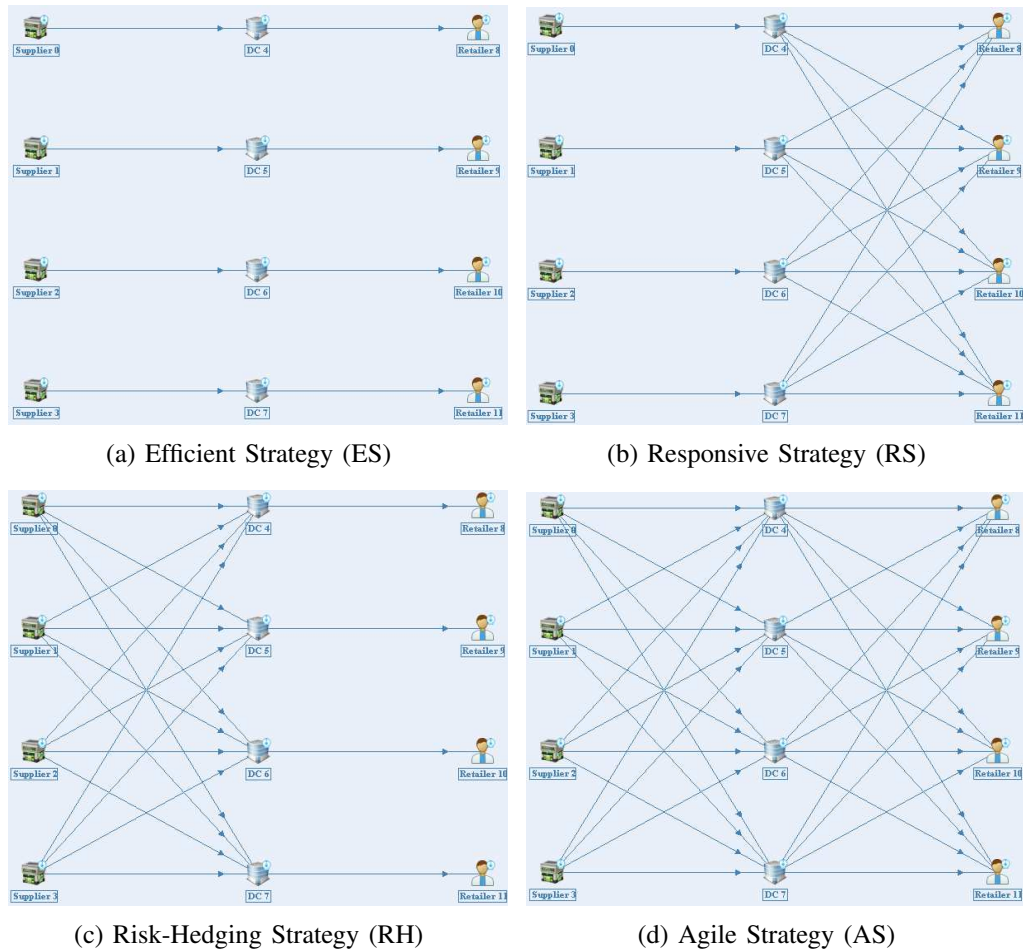(c) Risk-Hedging Strategy (RH)   (d) Agile Strategy (AS)

Figure 2: Three-tiers supply chain.

Figure 2 shows the three-tiers supply chains. The agents in each tier (from left to right) are the *supplier*, *distribution center* and *retailer*. The connections between the agents indicate material flows between the agents. The direction in the connection shows the flow of the products from the supplier to the retailer. The opposite direction represents the flow of the orders, from the retailer to the supplier. When the agent has more than one supplier, the order quantity is split evenly according to the number of suppliers available.

Based on the supply chain strategies in Section 2.1, we design four different SCN topologies, as shown in Figure 2. An efficient strategy (ES) seek to reduce redundant operations, by maintaining single connection from the suppliers to the retailers. Therefore we design a network topology with only one connection between agents in each tier. Figure 2(a) shows the network topology for the efficient strategy, with only single supplier for each agent in every tier. A responsive strategy (RS) is flexible to the uncertainty in

customer demands. This strategy distributes the demand among all distribution centers. The supply chain topology for responsive strategy is shown in Figure 2(b); each retailer is connected to four distribution centers. A risk-hedging strategy (RH) attempts to hedge the supply risk by having multiple suppliers, as shown in Figure 2(c). Hence the network topology has four suppliers for each distribution center. An agile strategy (AS) requires flexibility in all tiers. This is shown in Figure 2(d) with each retailer connected to four distribution centers, and each distribution center connected to four suppliers.

4 EXPERIMENT AND RESULTS

An agent-based simulation is developed based on the model described in Section 3. A three-tier supply chain is constructed with 12 agents, with four agents of each agent type (i.e, supplier, distribution center and retailer) in each tier. Different supply chain topologies are designed as shown in Figure 2. Experiments are conducted using the model to identify the suitable supply chain strategy for a particular risk scenario. The simulation parameters used in the simulation are defined in Table 1. Since we do not have another similar model with parameters, the parameters are designed based on our experiences on supply chain research and practice. We have performed preliminary validation of the model with a supply chain expert. However, a more systematic approach to validate the model is still required.

Table 1: Simulation parameters.

Parameter	Value
Back order Cost	0.2 (per unit per day)
Sale Lost Cost	$0.1 \times$ Sale Price (per unit)
Inventory Cost	0.1 (per unit per day)
Order Cost	100 (per order)
Operating Cost	100 (per agent per day)
Production Cost	20 (per unit)
Sale Price (Supplier)	40 (per unit)
Sale Price (Distribution Center)	50 (per unit)
Sale Price (Retailers)	60 (per unit)
Order Lead Time	1 day
Shipment Lead Time	1 day
Maximum Lead Time Delay	5 days
Initial Inventory	300 units
SQ Policy	$S = 200$ units, $Q = 300$ units

An agent incurs *back order cost* when the order is not fulfilled within the *order lead time*. When an order has expired, a *sale lost cost* is deduced. Each unit of the product also incurs *inventory cost* when the products are stored in the inventory. This represents the overhead cost of the warehouse rental and maintenance of the inventory. The *order cost* is the processing cost of generating a new order. Since each agent represents a business entity in the supply chain, the business operation also incurs an *operating cost* daily. The *production cost* is the cost of producing the products, which is 50% of the selling price at the supplier. Each tier increases the sale price by 10. When an order is sent to the supplier, it takes an *order lead time* to reach the supplier. After processing the order, the product shipment takes *shipment lead time* to reach the customer. The maximum allowed time before the order is expired is *maximum lead time delay*. Each agent has an initial inventory of 300 units. The agent uses the SQ policy to decide when to replenish the inventory, with the reorder level *S* and reorder quantity *Q*.

Four risk scenarios with different demand and supply rates are shown in Table 2. Constant rate is used to simulate no uncertainty in demand and supply. To simulate uncertainties, demand and supply are

modeled as normally distributed with a specified mean (μ) and standard deviation (σ). The normality assumption for the demand and supply is made based on literature (Nahmias and Olsen 2015).

Table 2: Demand and supply rates for different risk scenarios

Risk Scenario	Demand Risk	Supply Risk	Demand Rate (Unit per day)	Supply Rate (Unit per day)
DLSL	Low	Low	100	100
DHSL	High	Low	$N(\mu = 100, \sigma = 50)$	100
DLSH	Low	High	100	$N(\mu = 100, \sigma = 50)$
DHSH	High	High	$N(\mu = 100, \sigma = 50)$	$N(\mu = 100, \sigma = 50)$

The simulation is executed for 500 time steps which is determined empirically, and the warm-up period is estimated to be 100 steps based on the stable trends in the performance. The simulation is replicated for 30 runs, and the performance indices of the supply chain are averaged across the replications. The calculation of the performance indices is described in Section 2.3.

4.1 Results

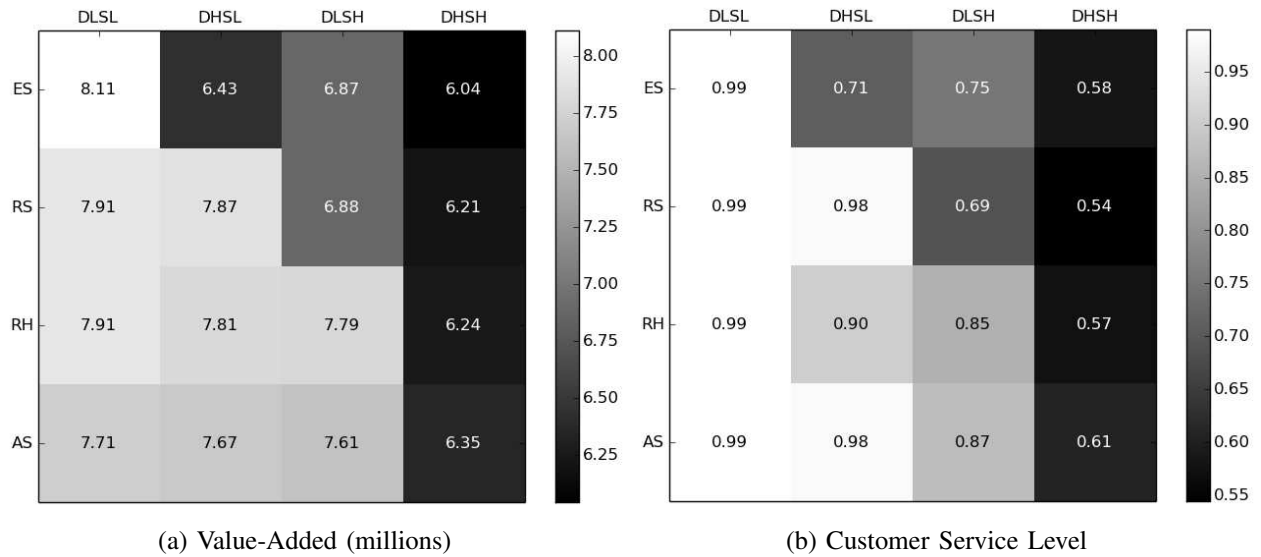(a) Value-Added (millions) (b) Customer Service Level

Figure 3: The heat map of performance indices for three-tiers supply chain under each risk scenarios. Each cell is shaded in gray according to the value of the performance. The intensity varies from white to black: white color indicates the best performance; while black color represent the worst performance.

Figure 3 shows the performance indices of different strategies under each risk scenario. The topology for each strategy is described in Section 3.2, and risk scenarios are defined in Table 2. Figure 3(a) shows the VA (in millions) of the supply chain in each cell, where the column indicates the different risk scenarios, and the rows represent different supply chain strategies. Each cell is also colored in shades of gray, varying from black at the weakest intensity to white at the strongest. Larger values are lighter shades of gray, while smaller values are darker. Similarly, Figure 3(b) shows the heat map of the CSL of the supply chain.

In the **DLSL** scenario, we examine the performance for different supply chain strategies by looking at the first column in both Figure 3(a) and Figure 3(b). The CSL is similar for all the strategies at 0.99. For efficient strategy, it achieves a profit of 8.11 million at the end of the simulation. The responsive and

risk-hedging strategies have lower VA (7.92 million). The agile strategy has the lowest VA among the strategies at 7.71 million.

Next, we look at the second column for the **DHSL** scenario, with uncertain demand. The efficient strategy is unable to handle the demand uncertainties and achieves a relatively lower CSL (0.71) compared to the DLSL scenario when the demand is stable. It also has the lowest VA (6.43 million) amongst the strategies. Risk-hedging strategy also has better CSL (0.9) compared to the DLSL scenario. Responsive and agile strategies able to achieve relatively higher CSL (0.98), with the responsive strategy having the highest VA (7.87 million).

The third column is the **DLSH** scenario, with supply uncertainties. Efficient and responsive strategies are unable to handle the uncertainty in the supply, resulting in lower CSL (0.75 and 0.69). This is also reflected in the lower VA (6.87) too. Risk-hedging and agile strategies have better CSL and VA than the efficient and responsive strategies. The agile strategy has lower VA than the risk-hedging strategy.

The last column represents the **DHSH** scenario, with uncertainties in both demand and supply. All the strategies are unable to handle the unpredictability in both the demand and supply; only the agile strategy has relatively better performance compared to other strategies.

4.2 Discussion

In the **DLSL** scenario, the demand and supply is stable. All strategies achieved CSL of 0.99, which indicates that most orders are fulfilled on time by each supplier. However, the topologies have varying VA performance. Except for the efficient strategy, all other strategies have lower VA as there are more orders created based on the number of suppliers for each agent. For example, the responsive strategy splits a single order at the retailer into four orders for each distribution center. As each order includes a fixed ordering cost, creating more orders incurs additional cost, thereby reducing the VA. This is more obvious for the agile strategy, with the highest degree of connection at each tier. It generates more orders at every tier. Hence efficient strategy is the most suitable strategy for this particular risk scenario with the highest VA.

In the **DHSL** scenario, the demand is unstable. The efficient strategy is unable to handle the demand uncertainties, which causes the supply chain to have more delayed and expired orders. The delayed and expired orders reduce the CSL. In addition, both the delayed and expired orders cause the low VA due to the back order cost and sale lost cost. Responsive and agile strategies increase the number of connections at the retailers, which distribute the fluctuating demand among all the distribution centers, as shown in Figure 2(b) and Figure 2(d). This allows both strategies to fulfill most of the orders, giving the highest CSL. Risk-hedging strategy also improves the CSL by splitting the orders at the suppliers; however it is not as efficient as distributing the demands at the retailers. Agile strategy has lower VA compared to the responsive and risk-hedging strategies due to the excessive orders created. For this particular risk scenario, we should use the responsive strategy which has the best performance in both VA and CSL.

In the **DLSH** scenario, the supply uncertainty is high. To handle the uncertainty in the supply, risk-hedging and agile strategies increase the number of suppliers for each distribution center. We can see four connections between the suppliers and distribution center in Figure 2(c) and Figure 2(d). Distributing the orders among all the suppliers enables them to fulfill more orders on time. However in terms of VA, the agile strategy still face the same problem of additional cost of generating more orders. Therefore the risk-hedging strategy should be used when the supply risk is high.

In the **DHSH** scenario, both the demand and supply risks are high. This instability causes many orders to be delayed and expired, resulting in lower VA and CSL for all the strategies. However, the agile strategy should be used when the demand and supply risk is high, as it has the best performance compared to other strategies.

Based on the results, the selection of strategy according to the demand and supply risk scenarios is summarized in Table 3.

Table 3: Selection of SCN topology based on demand and supply risk scenarios

		Demand Risk	
		Low	High
Supply Risk	Low	Efficient	Responsive
	High	Risk-Hedging	Agile

5 CONCLUSION

The complexity of the global supply chain presents a challenge to develop effective supply chain to mitigate risks in uncertain business environments. The issue of how to design suitable supply chain topology to handle demand and supply risk scenarios has not been well investigated. This paper describes an agent-based modeling approach for designing and evaluating the SCN topology for handling supply chain risks. A three-tier SCN model is developed based on typical supply chain distribution networks. Four supply chain network topologies have been designed to represent different supply chain strategies: efficient, responsive, risk-hedging, and agile strategies. Experiments have been conducted to evaluate the performance in terms of the value-added (VA) and customer service level (CSL) of the supply chain under different demand and supply risk scenarios.

From the experimental results, we can see that different risk scenarios can be handled to a certain extent by selecting the effective SCN topologies. In situation with low demand and supply risk, an *efficient strategy* with single supplier is the most suitable. To mitigate the demand risk, we should apply *responsive strategy*, where the SCN topology has with more connections between the distribution center and retailers. On the other hand when the supply risk is high, more connections to the suppliers are needed. So a *risk-hedging strategy* should be used in this scenario. When both the demand and supply risks are high, an *agile strategy* should be used, which has flexibility at all tiers.

In future work, further validation of the supply chain model will be conducted through real-world cases and benchmarking study with models in other researches. In addition, the impacts of the parameter settings on the supply chain performance and real-world complex supply chain networks will be analyzed. These will provide a stronger basis on promoting the use of agent-based simulation for supply chain design and risk management.

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