Decentralized Supply Chain Network for Emerging Issues Using Mechanism Design and Agent-Based Modeling

Vatsal Maru, Krishna Krishnan, Saideep Nannapaneni, and Ali Arishi

Department of Industrial, Systems, and Manufacturing Engineering
Wichita State University, Wichita, KS

Corresponding author's Email: vkmaru@shockers.wichita.edu.

Abstract: Supply chain network is one of the problems businesses come across when they are dealing with finished goods. From making the goods to providing them to the consumer is part of the supply chain. Considering the market size and 21st-century population demands, it is crucial to have the optimal design of the supply chain network. This research aims to optimize the supply chain network design in external dealings and provides insight into the decision-making framework. The experiments are performed in NetLogo for agent-based modeling and mechanism design to portray how the supplier and customer relationship behaves in relation to price and negotiations. The study provides promising insight into more negotiations that will reduce the prices for customers and that customers at least should wait out in the first negotiation round. Lower the auction, supplier benefits. With a lower number of auctions, suppliers can manage to sell more frequently as well. This study provides empirical evidence for decisions that can benefit various parties depending on their expectations and reduce certain roadblocks. The importance of reducing such roadblocks is even greater in the times of COVID-19 affected supply chains which are having continual effects.

Keywords: Supply Chain Design, Mechanism Design, Agent-based Modeling, Negotiations, Pricing.

1. Introduction

Supply chain networks have three design aspects. One is locating the entities in their respective echelon, the next one is the size and capacity of these entities, and the third is the distribution of products in the network itself (Simchi-Levi et al., 2008). The organization must decide to scale and reach their products, which we are not focused on in this paper, however. This research work focuses on delivering the products to customers (Maru, 2017) and the strategies which customers should employ to receive the best prices. In reality, there are multiple suppliers to a particular firm and there are multiple customers of a supplier firm. In this study, we focus on a customer having multiple suppliers and the scenarios in which they can minimize their buying prices while dealing with the suppliers. This study is focused on the distribution and sourcing of the supply chain design.

A supply chain network usually consists of a facility where the products are made (there could be multiple of them, however, for this paper and example, consider only one manufacturing facility), depending on the scale and reach of the organization, there will be distribution centers, followed by warehouses. Stores are optional in many businesses, for instance, if the organization is a business-to-business (B2B), then they can choose to supply to their customers even without having to open a store. Obviously, in the case of business to consumer (B2C) model, suppliers can have stores for selling their products. This research applies to both the models, B2B and B2C.

It is an important decision for customers to have a strategy while buying products. And for suppliers, it is the decision of how to distribute to reduce the costs. Many supply chain operate in centralized manner or Just-in Time Distribution (JITD). JITD as a concept is similar to Just-in-Time (JIT) management strategy that suggests inventory and product arriving in required quantity and at a required time to avoid higher inventory levels. JITD is a centralized system as the structure of decision-making in JITD requires customers to show their historical demands to suppliers and let suppliers deviate from the actual quantity of products requested and rather suppliers send the products based on their forecasting of what the actual demand could be. This structure requires open access to the information in the supply chain so that the end-users are satisfied. JITD operates such a way that there is no blockage of information, instead, the information flows freely(Simchi-Levi et al., 2008).

However, due to the changing modern dynamics and pandemic issues, there are increased challenges to centralized way of operations (Aday et al., 2020). Variety of industries are affected with increased uncertainty in their operations. Aday et al., (2020) provided food supply chain challenges pertaining to the pandemic (COVID-19). Mollenkopf et al., 2021 showed the challenge arising due to the changing supply chain that there are increased supply side road blocks and uncertainties are increasing. According to Mollenkopf et al., 2021, increased supply side uncertainty will increase buyer's lead time. However, there is no clarity on what decisions a buyer might rely upon to reduce the impact of lower and uncertain supply. Guan et al., 2020; Ishida, 2020 provided important insights in their papers. They suggested to leverage local and decentralized supply chain entities to overcome some of the supply challenges.

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This paper considers the above challenges part and provides solution in decentralized supply chain market that reduce buyer's lead times. Paper shows multi-agents participating in a market and what are the possible action scenarios for the suppliers and buyers. The paper proposes a mechanism design in which the supplier and customer agents interact with each other depicting the behavior of selling and buying. The proposed solutions will show the aspects and strategies by which the particular parties benefit. This in fact could be adopted as strategies for organizations in real life. In the next section 2, literature is reviewed to have an understanding of the field. There are different methodological approaches used in literature in regards to the supply chain. Section 3 is methodology for the research, section 4 is results and discussions, and ending with conclusion in the section 5.

2. Background

Eskandarpour et al., 2015; Farahani et al., 2014 provided a review of various research methods in the field. Both the papers review the supply chain design aspects using optimization methods. There is a significant requirement for multi-objective solutions and solutions which consider the product life cycle (Eskandarpour et al., 2015). Fan et al., 2003 provided the mechanism design overview on centralized and decentralized decision-making processes. They make the case of the decentralized system has its incentives aligned with the real-world scenarios compared to the centralized systems. Centralized systems need to seek permissions and work in collaborative manner that at times difficult to acquire.

Furthermore, Hennet & Arda, 2008; Raj et al., 2018 provided agent-based supply chain contracts for maximizing profits. The agent-based system is reviewed as the agent's performances differ in centralized and decentralized systems. In a centralized supply chain system the leader (dominant actor) usually gets the maximal value whereas the followers are maintained at the acceptable levels (Hennet & Arda, 2008). JITD also relates to the centralized entity, in other words, a dominant actor in the system.

Ishida, 2020 provided a holistic view on supply chains from two perspectives, pre and post pandemic (COVID-19). In their findings, considered for various industries, they suggested that the organizations have to be able to move from centralized system to decentralized system especially with regards to the disruptions that emerged due to the pandemic. Furthermore, Mollenkopf et al., 2021 suggested something similar for the food supply chains that they need to adapt and leverage local entities to further decentralize.

Similar insights can be found in the Guan et al., (2020), where the authors suggested that due to different COVID-19 policies in different regions, various entities attempting to follow the structures of pre-pandemic standards might have increased challenges. There are various industries and supply chains that are affected due to COVID-19 control measures. They also summarized that leveraging local and decentralized supply might help these reducing the effect of this pandemic.

In literature, decentralization is sought to overcome these challenges, however, there is a lack of framework that could work as a decision making framework for supply chain entities. Fan et al., 2003 provided a computational architecture using auction markets in mechanism design that showed how theoretically a decentralized mechanism design and auction markets could be set. According to them, decentralized approach opens solution space for improved market decisions. However, there is a lack of decision framework that provide a comprehensive decision making framework and understanding.

The above methods in the literature provide an idea of what to aim for in mechanism design considering the supply chain and also the importance of decentralization in the event of pandemic and especially under a highly challenging market. Decentralization resembles the real life incentives of different supply chain entities as otherwise in centralized system the dominant actor might get the biggest reward (Fan et al., 2003,). This paper aims to provide mechanism design that aim to reflect the real-life scenarios and cases in the event of different agent incentives. In this paper, an auction will be considered among customers and suppliers. These different entities can be considered individual agents (Sarmento, 2019). The next section provides a detailed methodology.

3. Methodology

This research studies the profit optimization problem of the supply chain network design in incentive-based decentralized system. The goal of the research is to provide a decision framework given the incentive structure for customers and suppliers. As mentioned in the above section, the entities can be represented as agents. Agents in the supply chain can be internal and external. Internal agents mean the entities of the same organization, such as a supplier's distribution center and a warehouse, whereas external meaning the organization and another organization which could be a customer. For this paper, we consider these agents to be external only.

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A. *Agent-based modeling*

The word agent is loosely defined in the literature. An agent could be any autonomous or independent entity such as a car, a human, an entity, etc. (Bonabeau, 2002). Mellouli et al., 2004 disputed and stood firm with a notion that for anything to be termed as an agent, it must learn from the environment. In computer science, especially in AI (Artificial Intelligence), agents are representing a learning behavior for autonomy and intelligence from the given set of policies on rewards. The above sentence loosely defines reinforcement learning. For this research, the agents are representing suppliers and customers and have certain constraints to perform in a system.

Agents are represented both in terms of customer agents, and supplier agents. Customer agents represent customers and similarly the case with supplier agents, which represents suppliers. The role of customer agents is to approach suppliers with demands, assess the proposal, update the demand based on buy or sell, and then approach again. Remember, the customer agents do not require to mandatorily buy the products in a given period. On the other hand, supplier agents receive the proposals and evaluate the price. If the price is acceptable, then the products are sent, and if not then they wait for another proposal in the subsequent periods. Quite normally, customers want to buy at the minimum price and suppliers want to sell quickly and at a high price.

B. *Mechanism design—Auction strategy*

Consider the following 5 step approach as the auction strategy between the agents.

Step 1: Customer approaches suppliers.
Step 2: If the supplier(s) can provide the demand, then assess the available options from which all suppliers can provide the demand
Step 3: Select the minimum price among the different prices
Step 4: Approach again with the minimum price to other suppliers if there are any
Step 5: Select the best price

The study considers two metrics to assess the results of the simulation. Average time to sell products and the buying price. The time is in units. For the simulation and modeling, NetLogo is used. NetLogo provides the flexibility of writing the code and simulate it in their user interface for visualization and inference purposes. In the NetLogo terminology, a unit time will be termed as “a tick”. And therefore, when there is a high number of ticks and sells, to understand the experiment results, we will not just use the buying price by customer agents but also the mean buying price as it provides the appropriate metric at the end of the simulation. Figure. 1 portrays the user interface. At this stage in fig. 3, it is difficult to read the terms, for which there will be additional figures provided in the results section. The purpose of fig. 3 is to show the simulation environment and user interface.

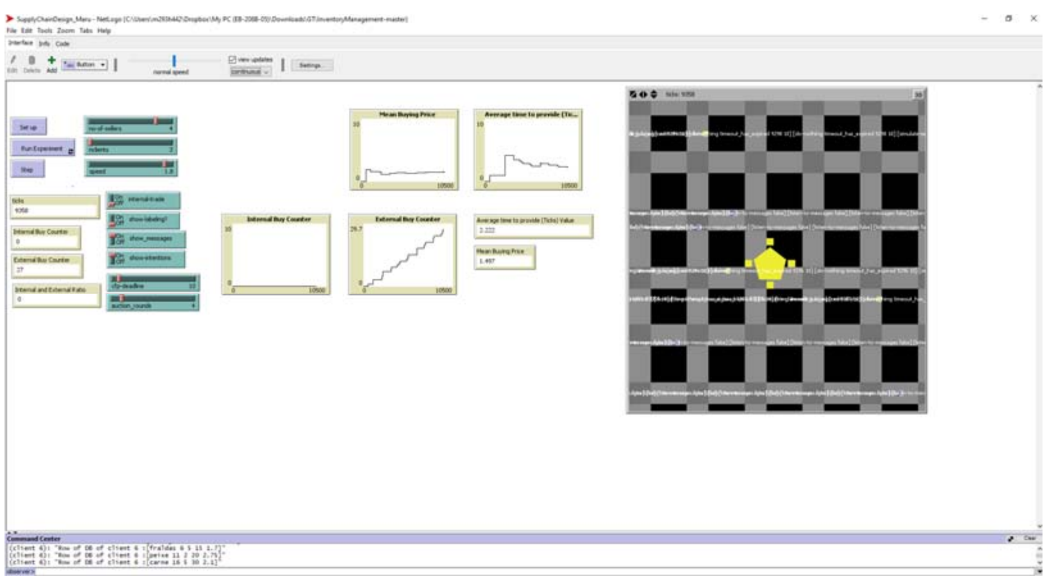

Figure. 1. The user interface of NetLogo software.

For concrete experimental results, the study considers the different predetermined number of auctions. This helps in understanding the negotiation parts in an auction. As a general rule, customers want low prices and they will negotiate much further on it, and suppliers want to sell keep to get the return on their finished goods. The next section considers three runs of the simulation with its results and provides relevant discussion which will lead up to the conclusion.

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4. Results and Discussion

A. First run

For the first run, the number of predetermined auctions was kept as 2 and the experiment was run over 9329 ticks. Figure. 2 shows the experiment results in the NetLogo. It is visible from figure 2 that the average time for suppliers to sell the products took 2.69 ticks and the buying price for customers was 1.33. The number of sales that happened during this run was 26 times.

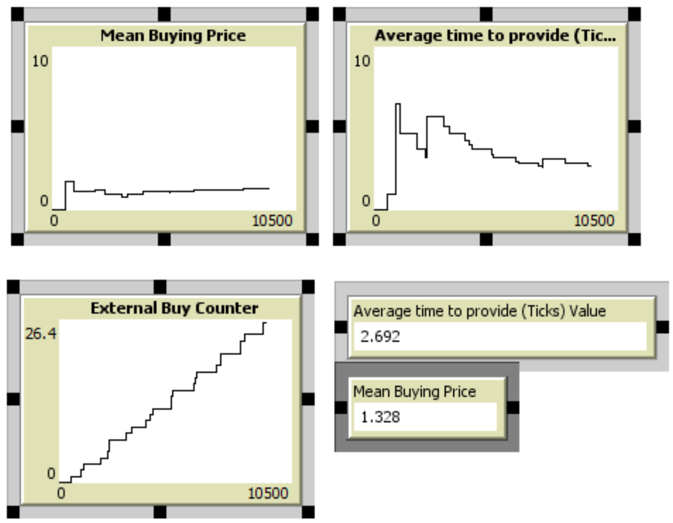

Figure. 2. Visual representation of values in the first run.

B. Second run

In the second run, the number of predetermined auctions was kept at 8 and the experiment was run over 9269 ticks. The results are provided in figure 3. The average selling time for suppliers was 9.25 ticks and the mean buying price was 0.77 for customers. The number of sales that happened during this run was 12 times.

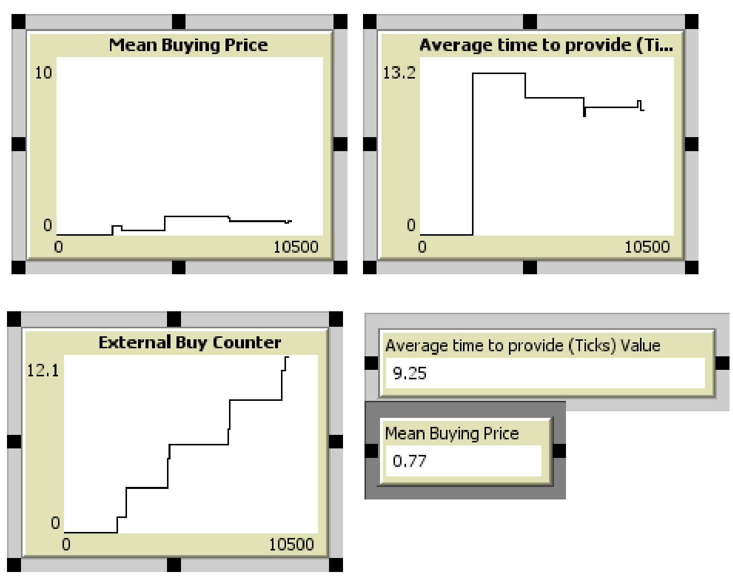

Figure 3. Visual representation of values in the second run.

C. Third run

The third run was performed to see whether the longer period of simulation has any different effects or we can expect similar results. This run, therefore, was run for 39323 ticks and the predetermined number of auctions was kept as

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2. Figure 4 shows that the average time to sell was 2.32 and the mean buying price was 1.34. The total number of times the sales happened was 117.

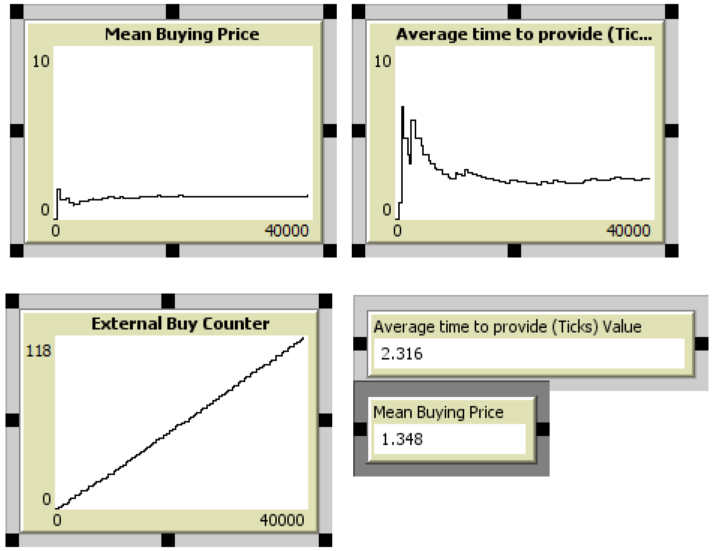

Figure. 4. Visual representation of values in the third run.

D. Discussion

During the several experimental runs, we can see the buying prices and the average selling time for certain predetermined auctions follow in similar ranges. However, for the average time, most times, it is higher, to begin with, and drops further over time. That is true to an extent for the mean buying prices as well. External buy means the total sales itself. It gradually increases, but its rate of growth does depend on the number of predetermined auctions. For a higher number of predetermined auctions, the steps are visible, and if the predetermined number of auctions are less, then the graph progresses towards having a straight line. In the next section, concluding remarks are given in regards to what these results mean for the suppliers and customers.

Due to the COVID-19 pandemic, a rising number of entities are facing supply chain obstacles. Agent-based along with the mechanism design approach provides a reliable decision making approach.

5. Conclusion

The experimental results show that when the predetermined auctions were low, the number of sales happened were high. This is particularly better for suppliers. Adding to that, when the predetermined number of auctions was low, the mean buying price was high too. That means with less or minimal negotiations, suppliers get a high price for their products and in less time (average time to sell). Suppliers can consider this input to receive better rewards in real-world dealings.

On the other hand, when the predetermined number of auctions was high, the customers received products at a cheaper rate. That means if the customer is not in hurry, then negotiating and stalling have a higher probability to get them the best possible price. If in hurry, then customers should at least wait out in the first negotiation as the visual graph shows the prices drop invariably.

Moreover, there is a little to no effect for longer simulation runs. 2 predetermined auctions make it apparent that even after almost 40,000 ticks, the mean buying price was high when negotiating less. This study is an important step forward for organizations to design the supply chain's last echelons. Revenue generation happens for organizations usually when dealing with external entities such as suppliers. And therefore, if they want to get the best return out of their products, then the ideal way would be to engage in fewer negotiations and quick selling. This situation reverses in the supply chain when the organization becomes a customer. As a customer, the organization would want to engage in as many negotiations as they could so that the buying prices are the lowest possible and in urgency go for at least two negotiation rounds as it has promising experimental results to show that the prices will drop.

The above insights provide a strategic foundational framework for the entities to follow depending on their incentives. Different incentives for supplier and buyer are also performed and the results show strong linear relationship as well.

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