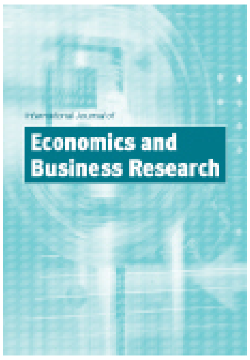

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Supplier selection strategies evaluation: a multi-agent based simulation

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Supplier selection strategies evaluation: a multi-agent based simulation

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Abstract: Local food systems have gained prominence in response to increasing consumer demand for locally produced food, driven by heightened interest in diet, food quality, sourcing, production methods, and food safety. These systems support the economic sustainability of small and medium-sized farms and promote consumer awareness through enhanced transparency and direct farmer-customer relationships. However, the effectiveness of these systems depends on robust and efficient supply chain operations, which are often hindered by the limited adoption of formal supply chain management practices. This study investigates the impact of farmers' local food system selection strategies and evaluates key performance metrics relevant to supplier assessment in local food networks. A theoretical multi-agent model was developed using NetLogo to simulate local food systems and analyse decision-making processes. Furthermore, this paper introduces an extended G-net model that integrates inheritance mechanisms into the G-net formalism, thereby enabling formal design and analysis of concurrent object-oriented systems. The proposed model preserves the foundational structure of Petri Nets, facilitating the use of existing analysis tools for simulation and verification. A case study is provided to demonstrate the model's utility; however, further empirical research is necessary to validate its practical application.

Keywords: local food system; multi-agent model; supplier selection strategies; performance metrics.

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1 Introduction

Food is essential to individuals as a source of energy. It is well known that healthy foods are important to developing an individual's mind and body. Thus, avoiding waste and damage to healthy food is imperative. Jedermann et al. (2014) noted that food damage occurs to approximately one-third of all food produced for human consumption, of which 15% occurs when distributing fresh fruits and vegetables. Gunasekaran et al. (2001) identified that industries in the USA waste roughly 30 billion dollars annually due to a lack of (or inadequate) coordination between supply chain partners. The main purpose of this research is to identify ways to mitigate or perhaps eliminate these damages. Fresh food is as fresh as possible during human consumption (Cadilhon et al., 2006). While there is no precise definition of locally produced food, its definition depends on geographical positioning or the distance between the supplier and consumer (Jones et al., 2004). The Alliance for Better Food and Farming defines local food as food that meets geographic and additional criteria related to social contexts, appropriate employment support, animal well-being, equitable trade, and environmental safety (Jones et al., 2004).

Local food systems (LFSs) have become more widely recognised as customers have grown more conscious of the dangers of industrialised foods, (e.g., reductions in crop variety and dependence on the use of insecticides and fertilisers) (Stroink and Nelson, 2013). An alternative approach involves locally producing foods to supply healthy, safe, and more nutritious food. Jones et al. (2004) noted several reasons for increased demand for locally produced food related to food deficiencies, customers' concerns surrounding food invulnerability, money savings, food freshness and safety, the healthiness of local food compared to traditionally produced food, environmental concerns, the treatment of farmers, local economic support and connections with farmers. This phenomenon has been a blessing for small and medium-sized producers, as they profit from higher prices and minimal constraints on volumes more than when trading through conventional wholesalers. On the other hand, such producers have started documenting a need for new markets and distribution channels to manage this increased demand efficiently and effectively while supporting customers' values (Krejci and Beamon, 2015). In particular, numerous producers face a lack of distribution facilities that can help them efficiently access retail, organisational, and marketing food services (Barham et al., 2012).

The main purpose of this work is to discuss the effects of different farmers' LFS selection strategies and to identify which performance metric should be considered by an LFS when evaluating suppliers. A discussion of the goals of farmers and food hubs is also provided, as the interviewed directors of food hubs show that they use informal supplier selection strategies by selecting suppliers based on their belief in their abilities to satisfy requests. There has been almost no research on ways to model LFS supplier selection strategies. Generally, it is widely indicated in the literature that multi-agent simulation (MAS) is a powerful means of exploring supply chain management and supply networks (Wooldridge, 2009). MAS is used to design and perceive complex systems (consisting of a set of independent and collaborating agents). Due to the nature and complexities of multi-echelon supply chains, MAS is an appropriate approach for simulating supply chain behaviour. MAS techniques are especially suitable (compared to classical research methods) for studying supply chains with distributed management and governance systems (like LFSs). A supply chain can be described based on its components, such as its goals, actors, operations, and relationships, and it is recognised that systems with these constituents and frameworks should be analysed with MAS tools.

Fulfilling consumers' requirements effectively is essential to success, and food value chains depend heavily on their suppliers to meet these requirements. Thus, an effective supplier evaluation and selection approach is essential to ongoing food value chain success. Several studies conducted in the business and production domains advise sellers to regularly and methodically measure suppliers' performance to work with suppliers that fulfil their requirements (based on performance metrics) and to thus adhere to company values and goals (Arabsheybani et al., 2018).

Despite the few studies conducted on LFS supplier selection and assessment, such processes seem to follow similar processes as those observed in other sectors. Food systems tend to apply improvised and impromptu methods to assess and select their suppliers (farmers) and do not track the performance of their farmers systematically or continuously due to the absence of frameworks and financial and human resources for food hubs that support suppliers' management processes. Nevertheless, food hubs face problems uniquely related to LFSs. As an illustration, LFSs are essentially based on many autonomous, small-scale farmers with widely differing goals, competencies, and decision-making tendencies, and they value their independence. Furthermore, an LFS is driven by classic supply chain metrics, (e.g., benefit maximisation) and community interest (e.g., local employment support). These concerns for the community services of local suppliers are based on human values, a wish to preserve powerful and diversified local supplies, and/or authoritative support (e.g., incentives) for local economic growth. A problem facing an LFS concerns determining a suitable approach to producer management that balances the two previous goals, which tend to clash. In other words, an LFS director wishes to determine the perfect number of farmers to collaborate with for every product to mitigate risks, supply clients with adequate stock, and guarantee satisfactory incomes for farmers. The LFS director also explores the development and management of strategies that satisfy their clients without making excessive demands from suppliers. Per capita, demand for fresh fruits and vegetables are constantly increasing while the number of small and medium-sized producers is continuously decreasing. It is thus necessary to discuss problems facing small and medium-sized suppliers in a systematic way to ensure the supply of high-quality fresh fruits and vegetables. Consequently, the assessment and selection of LFS producers is very difficult. Classical modelling methods are inadequate for analysing LFSs (Hill, 2010). MAS is the most suitable approach for studying dynamic interactions between independent, heterogeneous, and collaborating agents working in an LFS (Axtell, 2000). This work presents an LFS MAS framework in which multiple producers and a distributor cooperate, collect feedback, and gradually make adjustments. The proposed model is especially useful in testing the effects of different producer selection strategies based on system performance and structural changes over time. We adjust the model proposed by Bora and Krejci (2015) to elaborate on a supplementary approach to producer selection (a contract-based strategy). The proposed model assesses performance metrics for different supply chains by applying a delivery parameter to the assessment approach. We conduct a sensitivity analysis by varying multiple parameters such as shipping costs, weights of performance metric constituents, and the success of negotiation processes. This sensitivity analysis illustrates the proposed model and strategies and can help the LFS director make effective decisions.

In this work, we develop and apply an MAS model to an abstract LFS involving a food hub to assess the effects of three different supplier selection approaches on the performance of a particular LFS member and overall LFS performance. Performance is calculated by considering several supply chain metrics that can be conflicting. These metrics include pricing, delivery, quality levels, farm size distributions, and food hub dependence on suppliers. The model also determines the degree to which each selection strategy helps small and medium-sized farmers become economically self-sustaining (cost-effective and viable).

2 Literature review

This section reviews the literature on supply chains, supplier selection strategies, LFS chain management, LFS chain management challenges, and MAS.

2.1 Supply chain management

A supply chain is a system that connects an organisation to a set of suppliers to generate and dispense a particular product to purchasers. Thus, a supply chain system links suppliers, companies, contractors, wholesalers, retailers, and clients (Jiao et al., 2006). Several ways to enhance the performance and productivity of supply chains have been proposed (Van der Vorst et al., 2009), including the review of supplier selection strategies, the reduction of delivery times, the improvement of delivery techniques, the improvement of information transparency levels, the simplification of logistics simplification and the enhancement of coordination. Thus, the performance of a supply chain is measured to determine the impacts of these approaches. Determining a supply chain's performance allows the manager to select a suitable strategy to achieve their goals. Recently, while numerous companies have recognised the need to manage their supply chains effectively, they do not possess the knowledge to develop efficient metrics and measures for performance evaluation (Gunasekaran et al., 2001).

2.2 Supplier selection strategies

The performance of a supply chain depends on suppliers' performance and willingness to cooperate with other suppliers (Aragão et al., 2019). Figure 1 presents the supplier selection process (SSP) as an iterative process involving six phases (Hong et al., 2005).

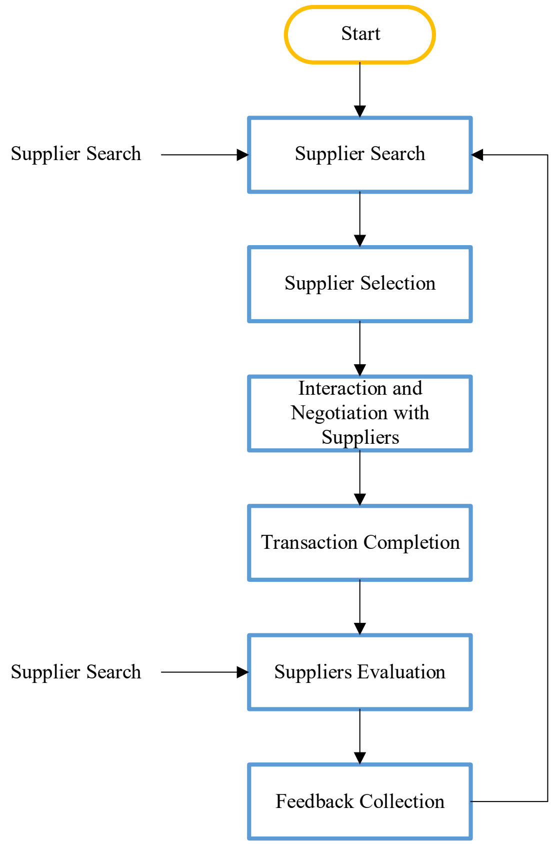
As illustrated in Figure 1, the SSP starts with searching for suppliers to satisfy customer demands. Then, suppliers are shortlisted according to the company's goals and supplier selection strategies. Suppliers are then contacted, and contract conditions are established. In phase four, the business transaction is completed, and in step five, the suppliers are evaluated, and the purchasing process occurs. In phase six, feedback on the purchasing process is provided to the suppliers.

We were interested in investigating how supplier selection strategies are developed. Our main findings are as follows:

- The selection of suppliers involves considering the advantages of strong connections.
- Quality and delivery are more important than costs.
- The most significant factor shaping supplier selection relates to quality and delivery consistency.

- Collaboration with suppliers is needed to satisfy users' demands and improve relationships between distributors and suppliers to enhance the quality of merchandise and delivery systems.

Figure 1 Supplier selection process (see online version for colours)



Accordingly, purchasers must follow particular strategies to select high-performing suppliers consistently. Supplier selection strategies help reduce negotiation time, maintain a stable list of suppliers, eliminate non-value-added costs, and achieve the shared goals of an effective supply chain (Van der Vorst et al., 2009). After agreeing on a supply chain management strategy for the suppliers' selections, suppliers and purchasers can cooperate to achieve the company's and supply chain goals.

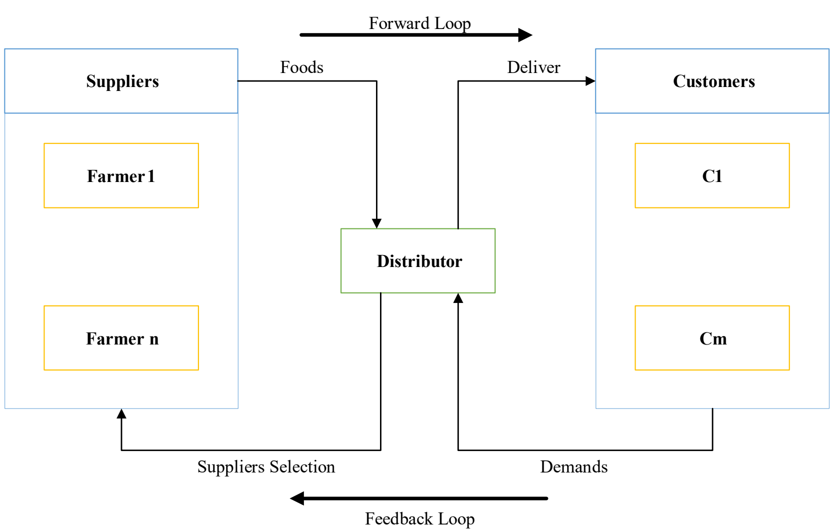
A supplier is selected based on the performance of existing suppliers. The literature recommends that distributors regularly and consistently evaluate the performance of their suppliers to ensure that suppliers systematically meet demands so that company goals are reached. Performance evaluations help purchasers remain competitive when selecting suppliers. Supplier selection strategies must enhance supplier abilities and performance (Krause et al., 2000).

Several models for evaluating supplier performance are proposed in the literature. Krause et al. (2000) categorise the approach to supplier performance evaluation into two categories: internal activity (the purchasing company is involved in or invests directly in manufacturing, purchasing capital, or process configuration) and external activity approaches (supplier selection by the external environment represented by the market to encourage competition). In this work, we focus on external supplier selection approaches. Some approaches to supplier selection involve clustering analysis, case-based reasoning, and data envelopment analysis (De Boer et al., 2001). However, these approaches are not used for final supplier selection and are only applied to filter certain suppliers out. Selection is performed via mathematical programming (allowing the purchasing company to develop an algorithmic goal program to select suppliers, increasing the value of some variables (quantity and quality) and decreasing those of others (delayed deliveries and prices)) and linear weighting (weights are assigned to variables based on their influence to help the purchaser determine the pros and cons of each supplier) (Hong et al., 2005). Contracts are also used when selecting suppliers. A contract helps a purchaser reduce risks (ensuring steady supplies of time, quantity, and quality) and helps a supplier generate additional profits (Van der Vorst et al., 2009).

2.3 Local food system chain management

Further investigations of LFSs are needed to put them on par with the latest technologies currently used in contemporary supply chains. LFSs cannot directly apply such methods due to an exclusive focus on purchasing companies' requirements, ignorance of suppliers' goals, market uncertainties, and limited merchandise lifecycles (Ahumada and Villalobos, 2009). Nevertheless, LFSs have attracted more attention due to growing demands for local food, governmental regulations, consumer concerns about their food, and claims regarding food quality (Marsden et al., 2000).

Figure 2 Local food system chain model (see online version for colours)



An LFS exhibits unique features that differentiate it from other supply chains. In an LFS, each farmer is autonomous and does not necessarily adhere to deals easily [dealers and farmers possess the same amount of power and can have conflicting goals, which decentralise decision-making (Aragão et al., 2019)]. The farmer's autonomy creates a challenge for LFS modeling. Furthermore, strategies focused on food freshness are mandatory for LFSs (Berdegúe et al., 2005; Van der Vorst et al., 2009). The LFS chain reconsiders the relationship between producers and consumers to demonstrate the relevance of traceability, transparency, and trust (Marsden et al., 2000). Figure 2 briefly overviews an LFS that a local distributor mediates.

The distributor usually prefers to work with small or medium-scale farmers; large-scale farmers cannot satisfy the rigorous quality needs of LFS customers, rendering the distributor powerless in the negotiation process (Berdegúe et al., 2005).

2.4 Local food system chain management

2.4.1 Challenges

LFS management faces two broad challenges: delivery, procurement, and quality.

- *Delivery:* Meixell and Norbis (2008) underscore several transportation challenges related to a lack of capacity, increased national and international sales, shipment sizes, and empty backhauling, as well as issues related to security, pollution, ecological conditions, and power, and they call for further studies on transportation selection. On the other hand, Mundler and Rumpus (2012) argue that most LFSs consume less energy than traditional food supply chains. However, Gunders (2012) attributes food damage occurring during transportation to inappropriate management and variable refrigeration, and they call for better frameworks and practices to prevent such losses. Stroink and Nelson (2013) found that many LFSs fail due to disorganisation, an absence of consistent supply chain management infrastructure, and early mistakes and ineffective practices. Agustina et al. (2014) noted that the main challenges facing LFSs involve avoiding delays in product delivery and reducing transportation costs without affecting farmers' benefits. Accordingly, delivery and transportation costs are central to an LFS's economic success (Bourlakis et al., 2014).
- *Procurement and quality:* there have been few studies on LFS performance and metrics (Bourlakis et al., 2014) and LFS supplier selection methods and procurement practices (Hong et al., 2005). In LFSs, the performance of suppliers depends on the methods used by farmers, and customer feedback must be provided quickly to incorporate customers' views into incoming procurements. Consequently, an investigation of LFS procurement and farmer selection methods is needed (Marsden et al., 2000; Michelle et al., 2013; Muldoon et al., 2013). Bourlakis et al. (2014) noted that in LFSs, consumers are more interested in information reinforcing transparency, trust, and traceability than information on farm locations or product management approaches. This information distinguishes the LFS from a traditional food supply chain and appeals to distinctive costs. Brannen (2013) affirmed that the main advantages provided by distributors and LFSs relate to their traceability (information related to product sources and production processes that can be readily tracked).

Levels of supply chain complexity are increasing due to constant increases in demand and the number of farmers involved in LFSs. Thus, a systematic approach to LFS challenges is required (Ting et al., 2014).

2.5 Multi-agent simulation

MAS is a novel technique for designing systems composed of autonomous and interacting agents (Macal and North, 2009). MAS is popular (Houhamdi and Athamena, 2021; Sun, 2018) because it:

- solves complex problems
- captures independent activities and collaborations
- use stochastic data
- identifies adequate solutions.

Sun (2018) defines an agent as a physical or virtual computing system that can perform tasks autonomously, perceive its environment, and interact with other agents to achieve global goals. MAS encodes agents' behaviors based on clear rules to display the outputs of interactions (Wilensky and Rand, 2015). An agent implicitly executes operations and makes decisions to achieve its goals. On the other hand, an agent must interact, coordinate, and negotiate with other agents. This feature distinguishes MAS from other simulation models (Balaji and Srinivasan, 2010; Houhamdi and Athamena, 2011). After reviewing the advantages of MAS over formal models (mathematics-based models), we found the following:

- MAS allows for a rational description of agents,
- MAS allows for the description of heterogeneous and autonomous agents,
- MAS allows one to model a solution to a problem, and its execution allows for the observation of results,
- MAS allows modelling agents' interactions using areas, networks, or both.

Nevertheless, MAS involves several steps to collect sufficient information because specific applications of the model usually provide insufficient information. Thus, a model that addresses the complexities that arise through communication between agents in supply chain systems is required (Macal and North, 2009). As an illustration, two agents communicate to negotiate costs. Assume that agent A is a buyer and agent B is a seller, agent B tells agent A their price, and if agent A accepts the proposed price, they purchase the goods; otherwise, a negotiation process will start where agent B sets a lower price for agent A. Agent A accepts the offer, negotiates further, or refuses the offer. MAS allows for a better representation of such complex interactions than formal models because MAS concepts reflect human cognition and language more closely than equations from formal models (Wilensky and Rand, 2015).

3 Methodology

In this section, we describe an MAS that models a theoretical LFS. The MAS is implemented using NetLogo (version 5.1.0). An LFS usually includes agents, (e.g., farmers, distributors, and consumers) who systematically collaborate in a progressive cycle of goods supply and a retrogressive cycle of information transfer/sharing. The agents coordinate and negotiate to achieve shared goals. We use NetLogo because it is user-friendly (it offers a simple interface) and allows for the modelling of complex systems such as supply chains (Chaudhry, 2016; Tisue and Wilensky, 2004). The description of agents and models is difficult (Grimm et al., 2006), and the standard design concepts and details (ODD) protocol is used to describe the proposed model.

This section describes the model's objectives, agents, framework, and submodel used.

3.1 Model objectives

The model addresses a challenge facing several LFS managers: supply chain inefficiency that is a direct consequence of managers' incapacities (or reluctance) to oversee farmer performance concerning quality, cost, and delivery. The LFS manager is interested in determining which strategies to apply to enhance LFS efficiency and measure these strategies' impacts on performance. Thus, the model aims to analyse the effects of multiple supplier selection strategies on LFS goals and farmers. Interviews with managers were conducted to evaluate the supplier's performance metrics (cost, delivery, quality, and relationships between farmers and vendors), and feedback was collected and incorporated into the model. Consequently, the model assesses the effects of the explicit consideration of supplier performance when selecting farmers in an LFS. This type of test is exclusively beneficial for LFS managers who do not use a consistent approach to selecting farmers and who solicit assistance based on the outcomes of supplier selection strategies.

3.2 Entities and variables

An LFS includes three actors: suppliers, a seller, and customers. The model focuses on relationships between suppliers (farmers), while those between the local seller (distributor) and customers are excluded. Rather, the distributor generates demand that represents the customers' demand. The model includes two types of agents: farmers and distributors (representing the LFS manager). The farmer produces food and seeks market channels, while the distributor purchases food from farmers to fulfil the demand.

Table 1 Farmers' categories

Profits	*Farm size*	*Farms ratio (%)*	*Sales ratio (%)*	*Weight (w)*
500,000+	Very large	3	56	4
250,000–500,000	Large	3	11	4
50,000–249,999	Medium	15	23	2
5,000–49,999	Small	79	10	2
	Total	100	100	

3.3 Farmer agent

The model includes 100 farmers distributed arbitrarily across a zone. The farmer's position is presumed to be fixed for all tests. The Euclidean distance is used to calculate the distance between a farmer and a distributor. Farmers are independent and operate autonomously to deliver food over one transaction cycle (seven days). There is no communication between farmers, and they cannot observe the other farmers' conduct or performance. Farmers profit from selling food to distributors and/or consumers (e.g., markets). A farmer belongs to a class size (very large, large, medium-sized, and small) depending on their profits, as shown in Table 1 (NASS, USDA, 2017).

While the distributor is the favoured market channel, farmers do not usually sell all their crops to the distributor to preserve their independence and avoid being entirely dependent on a single client. The farmer aims to increase profits while maintaining autonomy (independent from the distributor and customers). To determine the impacts of these clashing goals on a decision and a farmer's behaviour, each farmer is assigned a weighted aggregated utility function $U(t)$.

$$U(t_1) = 1 - e^{\left(\frac{-t_1}{R}\right)} \tag{1}$$

$$U(t_2) = 1 - e^{\left(\frac{-t_2}{R}\right)} \tag{2}$$

$$U(t) = \frac{U(t_1) + wU(t_2)}{1 + w} \tag{3}$$

Equation (3) calculates the $U(t)$ as the weighted sum. Equation (1) includes $U(t_1)$, which represents the utility gained by the farmer when t_1% of their total sales is given to the distributor. Equation (2) includes $U(t_2)$ representing the utility gained by the farmer when t_2% of their total sales are given to other customers. Note that $t_2 + t_2 = 100\%$ is based on the assumption that the farmer sells their full crop to the distributor or other consumers. $1/R$ is the risk level preferred by the farmer, and it is always positive (because the farmer is risk averse), and R represents the lowest income the farmer generates from sales of his entire yield at the lowest cost. The farmer's utility function $U(t)$ is represented by equation (3) as a weighted sum where w represents the utility weight of sales to customers except the distributor. w denotes the influence of these customers on the farmer. Weights are calculated by paired comparison (Onüt et al., 2009) where $w = 4$ denotes a strong impact (farmers managing large and very large farms view these customers as very influential) and $w = 2$ denotes a weak impact (farmers managing small and medium-sized farms view these customers as comparatively less influential).

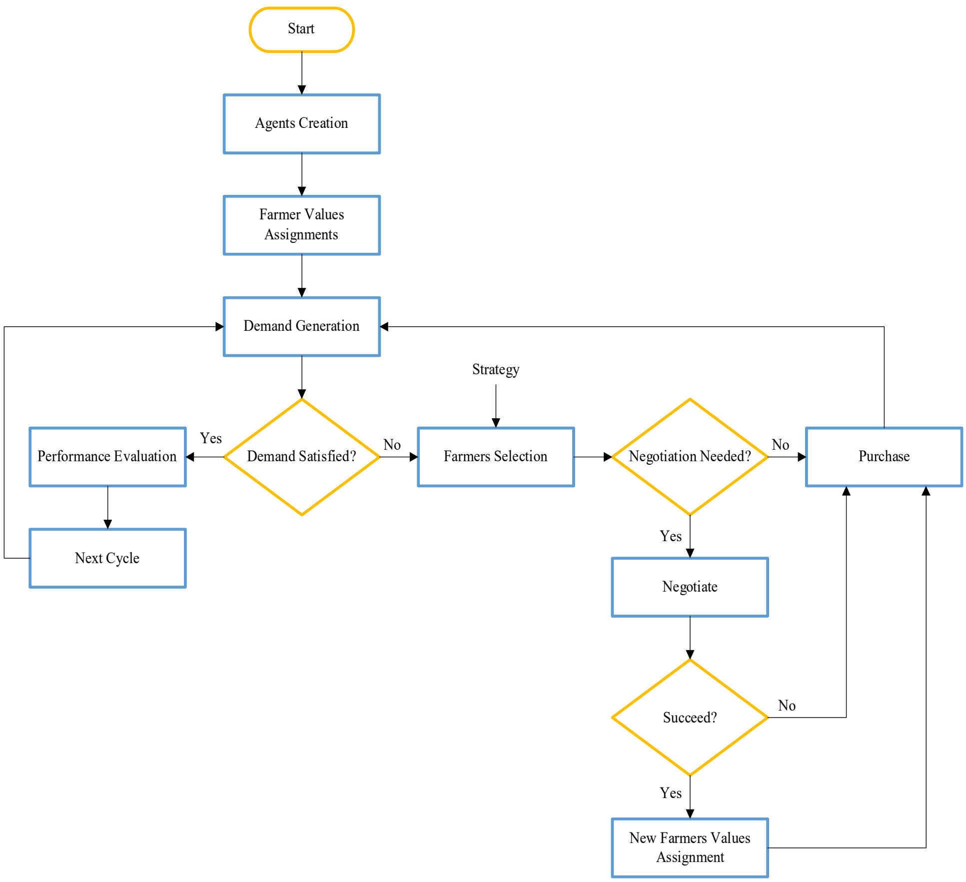
3.4 Distributor agent

In the simulation, only one distributor at the centre of the area is considered. The distributor's main goal is to ensure high-quality local food is sent to customers. Thus, food quality is considered when measuring the performance of suppliers. Nevertheless, the distributor must fulfil other requirements (considered in suppliers' performance metrics), such as each farmer's delivery times, and ensure that farmers comply with their schedules. Furthermore, the distributor is specifically encouraged to support small-and medium-sized farm farmers as a commitment to the community (Hill, 2010). One of the LFS's purposes is to purchase from these farmers whenever possible (Barham et al., 2012).

4 Model overview

During the distribution cycle, the distributor agent creates a demand list (as a representative of their customers). After demand generation, the distributor agent selects a set of farmers according to the chosen supplier selection strategy (these strategies are discussed in the following section). The distributor agent continues to nominate farmers until the demand is fully satisfied. The distributor then evaluates the farmers' performance. Figure 3 illustrates the algorithm. Note that the distributor agent operates as the model driver.

Figure 3 Algorithm description (see online version for colours)



After the creation of farmer and distributor agents, demand is created. This process is initiated by the distributor, who selects farmers according to three supplier selection strategies:

- Strategy 1: random selection
- Strategy 2: performance-based selection
- Strategy 3: best performance-based contracts.

After selecting a farmer, the distributor and farmer agents collaborate to determine if negotiation is required. After successful negotiations, the farmer is assigned new attribute values (prize, delivery, defects, and D ratio) according to the negotiation conditions. The distributor then purchases food from the farmer. When negotiations fail or no negotiations occur, the distributor purchases food from the farmer according to the current conditions. After the transaction is completed, the distributor verifies the demand. When demand is satisfied, the farmer selection process is complete, and the distributor then measures the farmer's performance, ending one distribution cycle. In the next cycle, the system generates new demand, and the cycle is repeated. However, when the demand is not satisfied, the distributor selects a new farmer, and the process is re-executed.

5 Model components

The model includes five components: configuration, farmer utility, performance measurement, negotiations, and supplier selection. The following section describes each component.

5.1 Configuration

The model is first established by creating the distributor and farmer agents, assigning their corresponding sites (positioning in the area), and initialising the values of farmer attributes. Each farmer's production value is fixed at 80%–100% (uniform distribution) of the highest crop volume needed to express the degree of uncertainty accompanying the yield. The portion of production a farmer wants to sell to the distributor, denoted as the D ratio, is fixed according to the farm size. Values of 1%, 1%, 5%, and 20% are assigned to very large, large, medium-sized, and small farms, respectively.

5.2 Farmer utility

After configuration, equation (3) calculates the value of farmer utility $U(t)$. Figure 4 shows $U(t)$ values perceived for a D ratio of [0%–100%] for farms of different sizes (very large, large, medium-sized, and small). Figure 4 sets threshold values for different types of farms. The thresholds are set to 0.505, 0.505, 0.450, and 0.325 for very large, large, medium-sized, and small farms, respectively. Values are calculated according to a survey conducted by the Wallace Center at Winrock International (NASS, USDA, 2017) showing that very large and large farms prefer to sell between 0%–13% of their crops to the distributor, medium-sized farms prefer to sell approximately 30% of their crop to the distributor, and small farms prefer to sell approximately 63%.

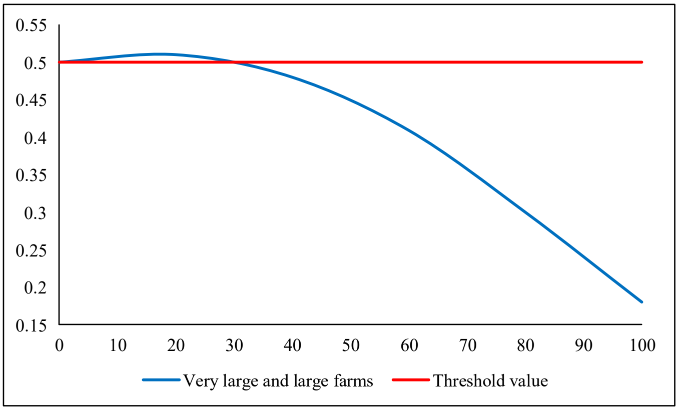
5.3 Performance

At the end of the distribution cycle, the distributor measures the performance of each farmer. Each farmer's performance is calculated based on five key parameters of the LFS. Equation (4) is used to calculate farm performance (P) as a weighted sum of the five parameters and Table 2 describes these parameters and their respective weights.

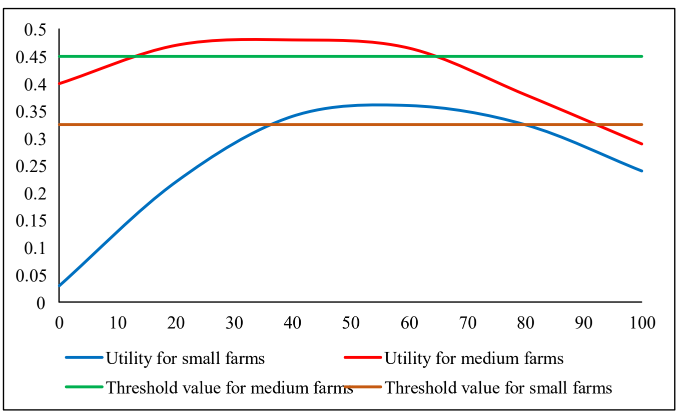
$$P = 0.1S + 0.1A + 0.15C + 0.3D + 0.35Q \tag{4}$$

where *S*: Farm size, *A*: Prior performance, *C*: Cost, *D:* Delivery, *Q*: Quality, and *P*: Farm performance.

Figure 4 Utility function for different types of farms, (a) utility function for very large and large farms, (b) utility function for different types of farms (see online version for colours)



(a)



(b)

Table 2 Performance parameters

Parameter	*Weight (%)*
Farm size (S)	10
Prior performance (A)	10
Cost (C)	15
Delivery (D)	30
Quality (Q)	35
Total	100

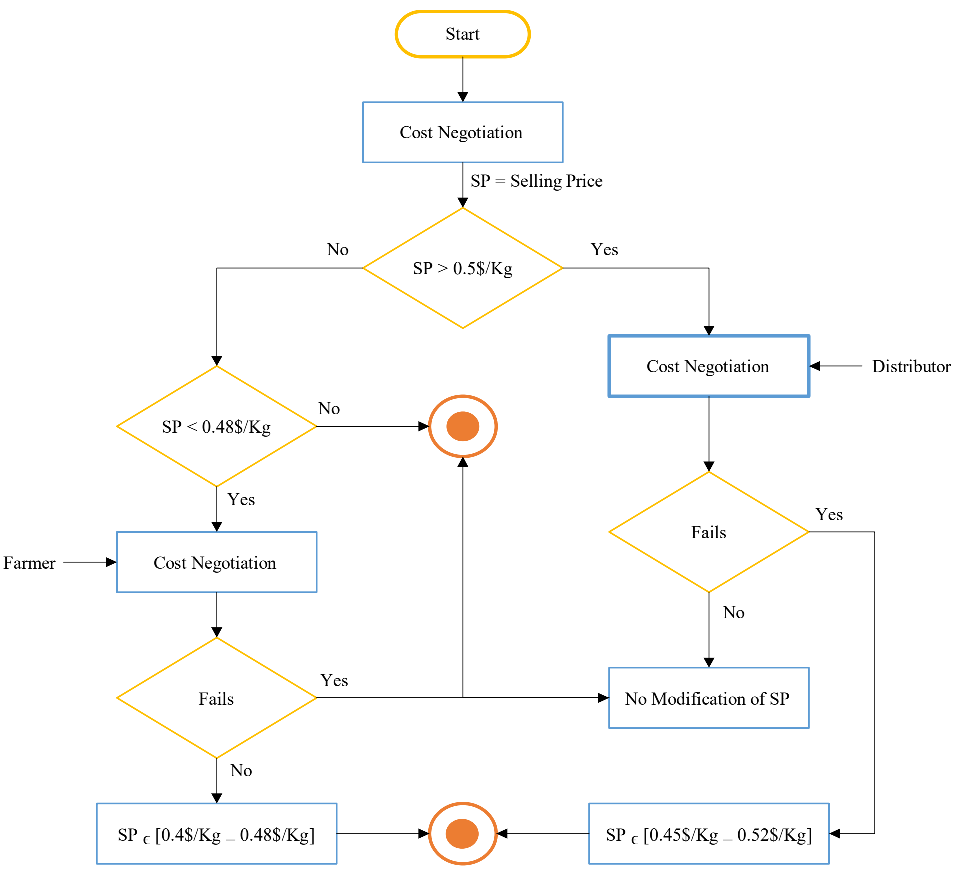
5.4 *Negotiations*

The distributor interacts with farmers to adjust one or several initialised values regarding food quantity, quality, and costs. We set the target rate to 75% for successful negotiations. We thus analysed sensitivity levels to study the impact of negotiation success rates on different supplier selection strategies. Both distributor and farmer agents can initiate a negotiation. The distributor initiates a negotiation to reduce the cost or enhance the food quality (for low or moderate quality levels). However, the farmer initiates a negotiation to increase costs or to modify food quantities (i.e., D ratio).

5.4.1 *Cost negotiation*

Figure 5 presents the algorithm for cost negotiations. For sales prices exceeding the expected price by 10%, the distributor initiates negotiations to decrease prices (2$/kg). When negotiations succeed, the selling price (SP) will range from 2$/kg to 2.3$/kg. However, when negotiations fail, the current prices are maintained. When the SP is lower than the expected price by 10%, the farmer negotiates to adjust the cost (2$/kg). When these negotiations succeed, the new SP will range from 1.8$/kg to 2.1$/k; current prices are maintained when they fail.

Figure 5 Cost negotiation (see online version for colours)



5.4.2 Quantity negotiation

When the farmer's utility is lower than the threshold utility value, the farmer initiates negotiations to increase or decrease the supplied quantity of food. An augmentation/ reduction (Δ) of the D ratio of 0.1%, 0.1%, 2%, and 5% is applied to very large, large, medium-sized, and small farms, respectively. Δ is negative when the D ratio is high. For instance, in Figure 4, for a small farm, note that when the farmer's utility is less than 0.325 (the threshold value) and when the D ratio is 95% (the farmer supplies a higher quantity than he prefers), Δ is negative. However, when the farmer's utility is less than the threshold, and D_ratio is valued at 20% (the farmer supplies a lower quantity than he prefers), Δ is positive. In each negotiation phase, the D ratio is modified by Δ.

5.4.3 Quality negotiation

This form is exclusively initiated by the distributor to enhance the quality of food farmers produce. This negotiation is only performed when food supplied by farmers is damaged (poor quality). The distributor asks farmers producing low-quality food to upgrade their food quality from low to medium. In contrast, farmers of medium-quality food are asked to upgrade their food quality from medium to high. When such negotiation succeeds, the farmers improve the quality of their food. While high-quality farmers do not need to upgrade the quality of their food (as their food is already considered of good quality), the distributor negotiates with these farmers by sending their comments (regarding observed deficiencies) to these farmers to consider them for the following distribution cycle.

5.4.4 Supplier selection

The present study focuses on this component, and the proposed model contributes to our understanding of the impacts of a particular supplier selection strategy on performance metrics of the LFS. According to the distributor's goals, performance metrics include the number of selected farmers and their positioning in the given region, farm sizes, farmer performances, the ratio of farmer crops supplied to the distributor, farmers' consistencies, and the number of negotiations between the distributor and farmers. We consider the following supplier selection strategies:

- *Strategy 1:* Random selection. This strategy is a popular strategy used by many distributors. The manager randomly selects farmers to satisfy demands.
- *Strategy 2:* Performance-based selection. For this strategy, the distributor considers performance levels when selecting farmers. The distributor evaluates the farmers' performance at the end of each distribution cycle and ranks them by their performance. In the next distribution cycle, the distributor selects farmers based on their rankings and makes calculations at the end of the previous distribution cycle. Selection is performed based on rankings until demands are satisfied. When farmers are equally ranked, selection is done randomly.
- *Strategy 3:* Best performance-based contracts. Contracts are important for ensuring adequate and methodical supplies, building relationships, limiting the number of negotiations held, and promoting commercial and professional procedures. According to this strategy, the distributor selects farmers based on their performance and then contracts with them for a particular period. In other words, farmers

performing better than the threshold level (for our simulation, the threshold is set to 97%) during the assessment cycle (for our simulation, the assessment cycle is set to 20 distributions) receive a contract for the next 20 distribution cycles. We assume that all farmers accept such contracts. When contracted farmers cannot satisfy demand, non-contracted farmers are selected based on their performance (as in strategy 2) to satisfy the leftover demand. According to this strategy, contract constraints related to quantity, quality, and pricing are fixed (we assume that the farmers maintain these constraints for the entire contracted period). Note that negotiations cannot be held during the contract period.

These three strategies are simulated to evaluate their performance according to LFS metrics. Note that the tests are experimental, and we assume that the model follows only one strategy.

6 MAS result discussion

A simulation of our model was conducted by running a set of experiments to assess the impact of the three strategies on LFS performance metrics. Metrics considered in the simulation are derived from the distributor's goals and economic conditions. These metrics include the number of selected farmers, the distribution of farm sizes, average farmer performance levels, the number of farmers requiring negotiation, the percentage of scheduled deliveries, benefits provided by the distributor, and the volume of food supplied by farm size. The simulation involved 30 rounds of 150 distribution cycles and an initial period of 75 distribution cycles.

Table 3 Performance metrics

Metrics	*Strategy 1*		*Strategy 2*		*Strategy 3*	
	M	*SD*	*M*	*SD*	*M*	*SD*
Total selected farms	52.96	1.14	58.76	7.98	35.95	3.30
Very large farm	1.63	0.09	0.29	0.37	0.37	0.33
Large farm	1.63	0.10	0.11	0.17	0.19	0.13
Medium farm	8.14	0.17	11.76	1.23	5.82	0.78
Small farm	41.57	1.08	43.57	8.53	29.89	3.27
D ratio – very large	0.09	0.00	0.03	0.04	0.03	0.03
D ratio – large	0.09	0.00	0.02	0.02	0.03	0.02
D ratio – medium	0.37	0.02	0.31	0.01	0.44	0.00
D ratio – small	0.35	0.02	0.37	0.03	0.65	0.02
Distributor benefits	2923	275	4126	146.5	4166	140
Negotiation	15.84	0.89	11.43	2.40	6.95	1.36
performance	0.84	0.01	0.98	0.00	0.98	0.00
% of quality	9.33	0.44	4.96	0.31	5.05	0.46
% of scheduling delivery	67.36	2.32	99.60	0.43	93.19	1.57

Performance metric values for the three strategies are given in Table 3 (where *M* = mean value and *SD* = standard deviation), which clearly shows that the three strategies are completely distinct regarding these metrics.

To determine if the distinctions perceived between these strategies have statistical significance ($\alpha = 0.05$), a t-test was applied to the mean values of all metrics of the last distribution cycle. Table 4 shows the results and clearly shows that strategy 1 is worse than strategies 2 and 3. Thus, the distributor must carefully consider adopting these two strategies when selecting supplier farmers.

6.1 Farm size

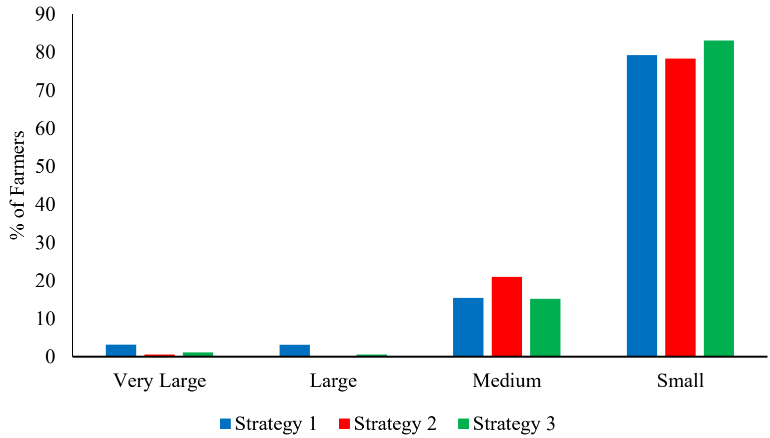
The distributor's main goal is to benefit farmers who are managing small-and medium-sized farms. The distributor must determine how certain strategies can help them achieve their goals. Figure 6 illustrates that for strategy 1, the distributor applies values of 4%, 4%, 16%, and 76% for very large, large, medium-sized, and small farms, respectively. This distribution is comparable to the USDA's observations (NASS, USDA, 2017). However, strategies 2 and 3 contribute to this goal. Under strategy 2, crops usually originating from very large and large farms are collected from medium-sized farms. Under strategy 3, the crops usually originating from very large and large farms are collected from small farms. Simulation results show an insignificant difference (*p-value* > 0.05) between the number of farmers selected under strategies 1 and 2. On one hand, the difference between the number of chosen farmers under strategy 3 and strategies 1 and 2 is notable. Accordingly, the supplier selection strategy adopted significantly shapes the number of farmers involved.

6.2 Farmer sales

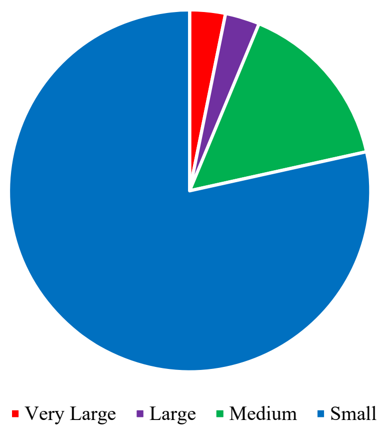
The distributor seeks to help their farmers increase their sales. According to the survey (Grimm et al., 2006), farmers of smaller farms sell 39% of their crops to a distributor and wish to increase this value to 63%. Strategies 1 and 2 allow for an increase in the sales of small farmers to 35% and 38% to the distributor on average. Nevertheless, strategy 3 allows farmers of smaller farms to sell up to 62% of their crops to the distributor. For farmers of medium-sized farms, 37%, 30%, and 47% of sales are directed to the distributor under strategies 1, 2, and 3, respectively, as shown in Figure 7. Strategy 3 increases farmers' sales due to contractual constraints, allowing farmers to sell a predetermined quantity of crops, which takes 20% of the sales as their earnings. In our simulation, when customers receive inadequate products, the distributor must reimburse the expense to the customers (considered a loss).

Consequently, benefits are calculated by subtracting losses from earnings. As shown in Figure 8, average benefits for the distributor adopting strategies 2 and 3 are roughly 35% more significant than those achieved by adopting strategy 1. As a well-known business practice involves providing incentives to the best suppliers (Cachon and Lariviere, 2005), some of the benefits are distributed between high-performing farmers. The rewards can take different forms, such as money, permanent contracts, or price inflation. Such incentives encourage farmers to improve their performance and consequently enhance the quality of their products and the supply chain. In our MAS, rewards are permanent contracts (strategy 3).

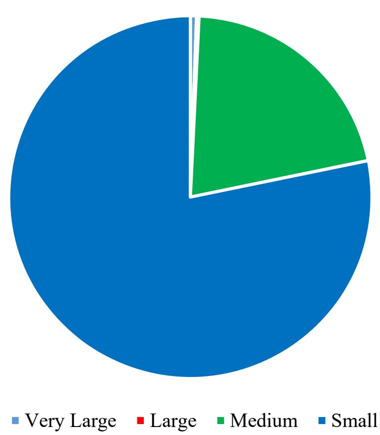
Figure 6 Farmer distribution, (a) farmer distribution by farm's size, (b) strategy 1, (c) strategy 2, (d) strategy 3 (see online version for colours)



(a)

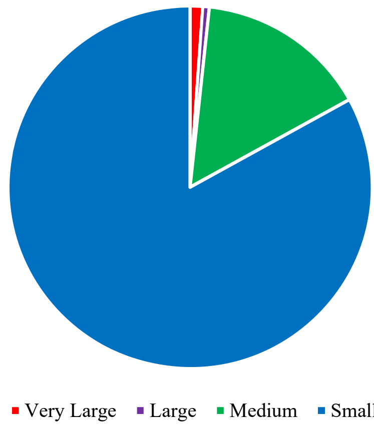


(b)



(c)

Figure 6 Farmer distribution, (a) farmer distribution by farm's size, (b) strategy 1, (c) strategy 2, (d) strategy 3 (continued) (see online version for colours)



(d)

Figure 7 Farmers' sales (see online version for colours)

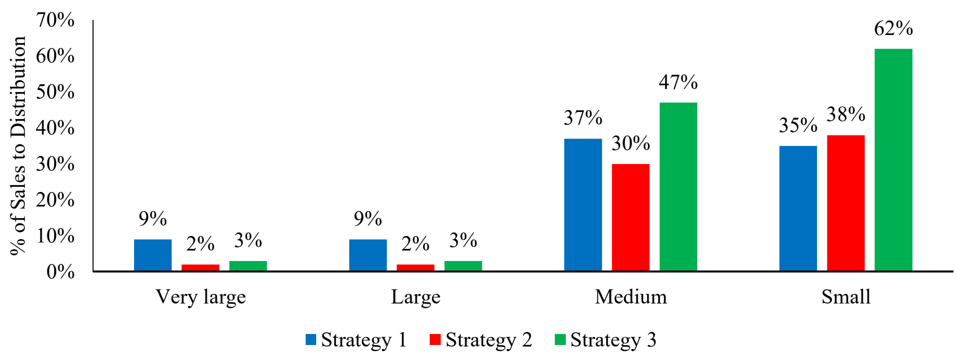


Figure 8 Distributor benefits (see online version for colours)

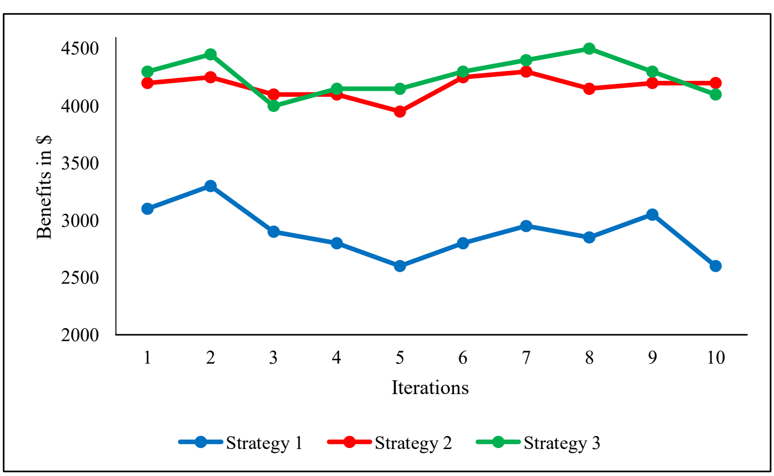
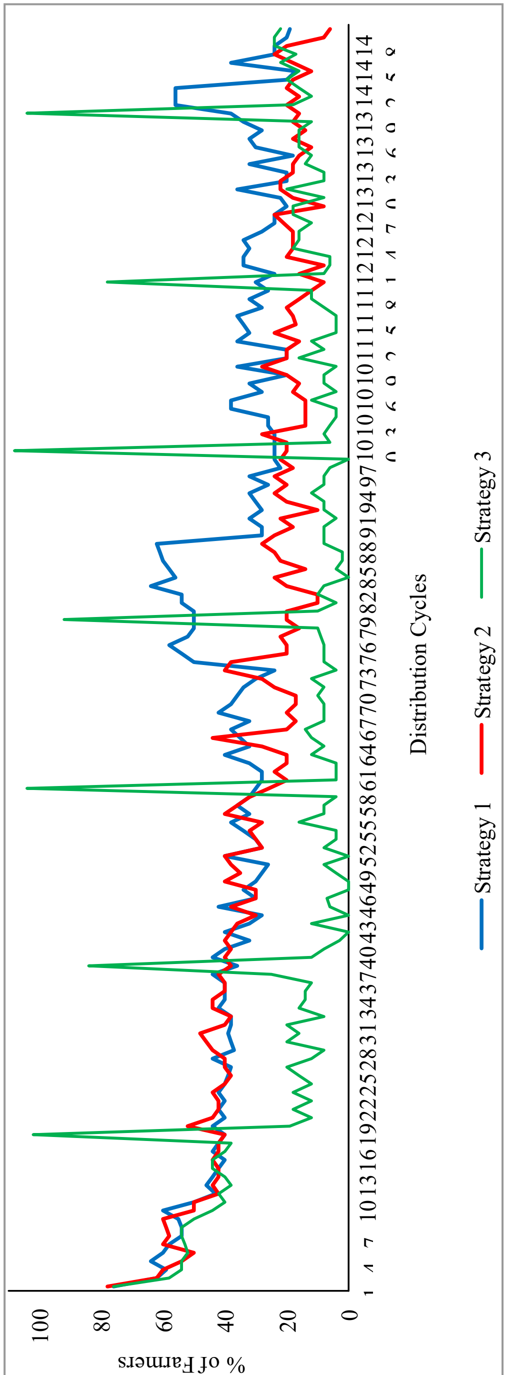


Table 4 Comparison of strategies

Metrics	*Strategy 1 vs. strategy 2*		*Strategy 1 vs. strategy 3*		*Strategy 2 vs. strategy 3*	
	P-value	*Result*	*P-value*	*Result*	*P-value*	*Result*
Total selected farms	0.21	Identical	0.00	Best = Strategy 1	0.00	Best = Strategy 2
Very large farm	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.38	Identical
Large farm	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.08	Identical
Medium farm	0.00	Best = Strategy 2	0.00	Best = Strategy 1	0.00	Best = Strategy 2
Small farm	0.29	Identical	0.00	Best = Strategy 1	0.00	Best = Strategy 2
D ratio – very large	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.44	Identical
D ratio – large	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.03	Best = Strategy 3
D ratio – medium	0.00	Best = Strategy 1	0.00	Best = Strategy 3	0.03	Best = Strategy 3
D ratio – small	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.00	Best = Strategy 3
Distributor benefits	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.15	Identical
Negotiation	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.00	Best = Strategy 3
performance	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.09	Identical
% of quality	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.19	Identical
% of scheduling delivery	0.00	Best = Strategy 2	0.00	Best = Strategy 3	0.00	Best = Strategy 2

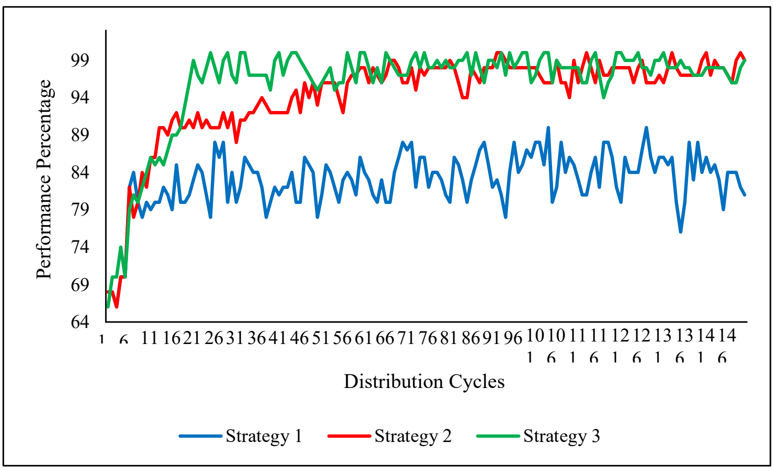
Figure 9 Negotiation percentage (see online version for colours)



6.3 Negotiations

The percentage of farmers who negotiate with the distributor in each distribution cycle is shown in Figure 9. Strategy 1 requires relatively more negotiations than strategies 2 and 3. However, under strategy 3, many peaks occur, and negotiations sometimes involve up to 110% of farmers. In Figure 9, at distribution cycle 60, the percentage of negotiating farmers is 104% (29 farmers negotiate with the distributor, but only 28 succeed and are selected). Remember that since the contract period includes 20 distribution cycles, the peak in strategy 3 appears after each contract period (except during regular contract renewals, where the percentage ranges from 0%–27% under strategy 3). For strategy 1, the interval ranges from 14%–45%, while for strategy 2, the percentage ranges from 6%–35%.

Figure 10 Performance comparisons (see online version for colours)



6.4 Performance

The average number of farmers adopting strategies 2 and 3 is significantly higher than the number adopting strategy 1 (see Figure 10) due to the random selection of farmers, leaving no control mechanism for guaranteeing food quality. On the other hand, under strategies 2 and 3, farmers are chosen based on their performance, and thus, supply chain performance is gradually improved.

6.5 Quality

In each distribution cycle, 7%–10% of farmers supply imperfect products, as strategies 2 and 3 involve far fewer quality problems (2.78 and 1.85, respectively) on average than strategy 1 (4.93). Figure 11 shows that under strategy 2 (strategy 3), 5.96% (5.04%) of farmers provide non-compliant food. However, under strategy 1, 9.46% of farmers, on average, supply imperfect food. The instability perceived in Figure 11 for quality imperfection is attributable to the random nature of farmer quality. It is very difficult to predict which farmers are involved, the number of farmers involved, and when they can provide low-quality products. The following graph reflects this random feature of MAS.

Figure 11 Quality issues (see online version for colours)

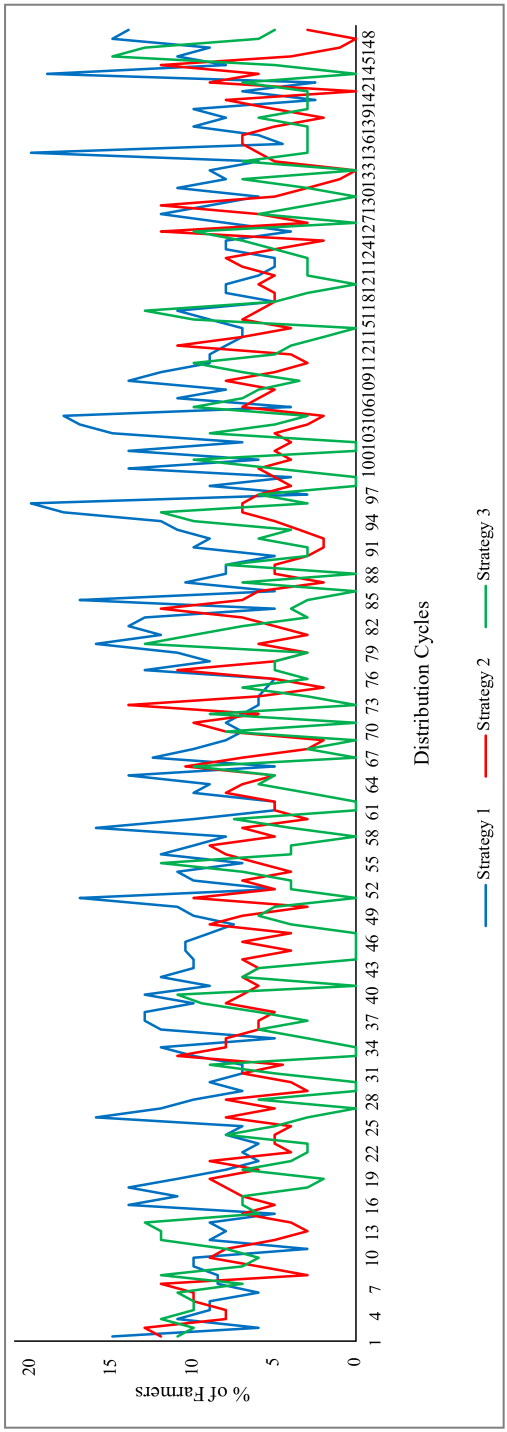
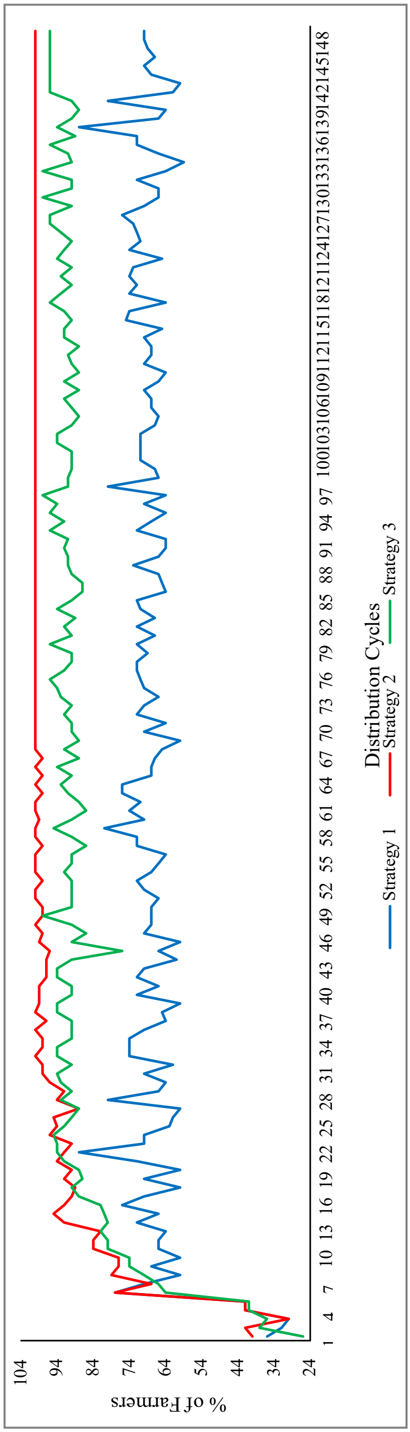


Figure 12 Delivery scheduling (see online version for colours)



6.6 Delivery scheduling

The average percentage of farmers that schedule their deliveries under strategy 1 is 67%, which is relatively higher than the initial MAS values (belonging to [25%, 45%]). This results from communication and negotiations between the distributor and farmers on delivery schedules. Note that it is impossible to follow the schedule fully. Furthermore, asking farmers to schedule their deliveries is challenging for the distributor, even though delivery schedules significantly benefit the distributor's activities.

On the other hand, the percentage of farmers scheduling deliveries is considerably high under strategies 2 and 3 as shown in Figure 12. Under strategy 2, this value is approximately 100% as a direct consequence of the incentive to be selected when farmers start scheduling their deliveries. However, under strategy 3, the percentage of farmers who schedule their deliveries is 93%, less than that measured under strategy 2 but much higher than that measured under strategy 1. It seems that after a farmer receives a contract for a certain period, he occasionally fails to adhere to the contract constraints, and the distributor is not presented with many alternatives. Thus, the distributor must consider this issue when adopting a specific strategy.

Finally, strategies 2 and 3 surpass strategy 1 regarding most performance measures and distributor goals. Accordingly, the distributor benefits considerably from shifting from strategy 1 to strategy 2 or strategy 3. Strategies 2 and 3 adopt almost identical measures and diverge concerning eight metrics as illustrated in Table 3: the number of selected farmers (managing small and medium-sized farms), the percentage of crops delivered by farmers (managing small and medium-sized farms), the number of negotiations held, and the percentage of farmers scheduling their deliveries. While these two strategies differ slightly, each outperforms the other for the remaining metrics. Consequently, before selecting the two strategies, the distributor must consider other parameters, such as negotiation and contract costs.

7 MAS sensitivity analysis

Model robustness is crucial when analysing a model's sensitivity and understanding LFS performance when the values of LFS inputs are modified. For our MAS, we modified the following parameters individually (one by one), and we examined the corresponding effects on LFS measures:

- *Transportation cost:* 0.31\$/km. We were interested in evaluating the effects of transportation costs on system viability.
- *Weights of performance parameters:* initially, farm sizes were considered in our performance estimations. We here wish to evaluate their impacts on LFS performance by setting the size to null. Thus, the weights are as follows: $S = 0$, $A = 10$, $C = 25$, $D = 30$ and $Q = 35$. We also seek to measure the impacts of costs on system robustness by increasing the cost weight. The weights are set to: $S = 5$, $A = 20$, $C = 35$, $D = 20$ and $Q = 20$.
- *Negotiation success rate:* initially, in our MAS, we set the success rate for negotiations at 75%, but we are interested in investigating the impacts of 100% and 50% success rates.

- *Contract period:* For strategy 3, we analysed the impact of the contract length on LFS performance by increasing the period to a value of 30 (roughly seven months).

The following section discusses the sensitivity analysis conducted on the three strategies, where:

- $T1$: Transportation cost = 0.31$/km
- $T2$: $S = 0$, $A = 10$, $C = 25$, D = 30 and $Q = 35$
- $T3$: $S = 5$, $A = 20$, $C = 35$, D = 20 and $Q = 20$
- $T4$: Negotiation success rate = 100%
- $T5$: Negotiation success rate = 50%
- $T6$: Contract period = 30.

7.1 Distributor benefit

Figure 13 shows the simulation results; the distributor's benefit is not significantly affected by modifications made to the metrics. The distributor's benefit depends heavily on customer demand. Nevertheless, for the initial MAS, the results of strategy 2 show a slightly stronger benefit. Under other MAS settings, strategy 3 generates slightly stronger benefits.

7.2 Delivery

Figure 14 show that sensitivity analyses do not considerably affect the average delivery.

7.3 Performance

Figure 15 show that modifications of the metrics do not affect the average level of farmer performance.

Figure 13 Distributor benefit analysis (see online version for colours)

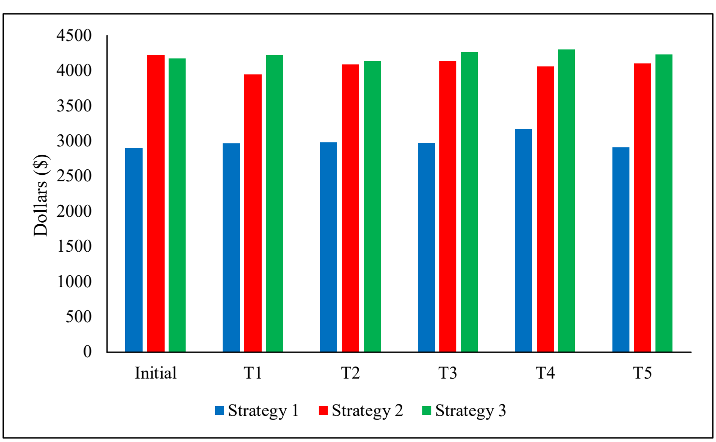
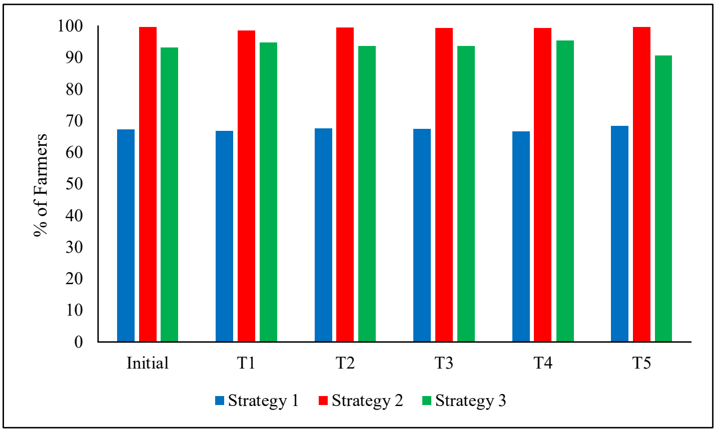


Figure 14 Delivery analysis (see online version for colours)



7.4 *Negotiation*

Figure 16 confirms a considerable impact on the total number of negotiations. The increase in transportation costs (*T*1) increases the average number of negotiations under the three strategies. This is attributable to frequent and repeated negotiations between small-scale farmers and distributors to augment their sales, particularly under strategy 2. On the other hand, when the success rate is reduced to 50% (*T*5), Figure 16 shows an insignificant augmentation in the average number of negotiations.

7.5 *Defects*

Figure 17 shows an insignificant modification of the number of defects supplied by farmers under the three strategies (excluding strategy 1 for the case *T*5). The reduction in defects observed is essentially attributable to the success of negotiations.

Figure 15 Performance analysis (see online version for colours)

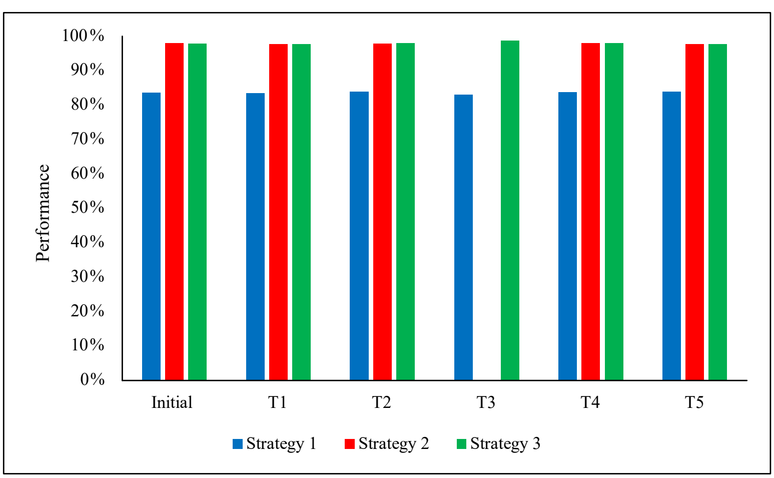


Figure 16 Negotiation analysis (see online version for colours)

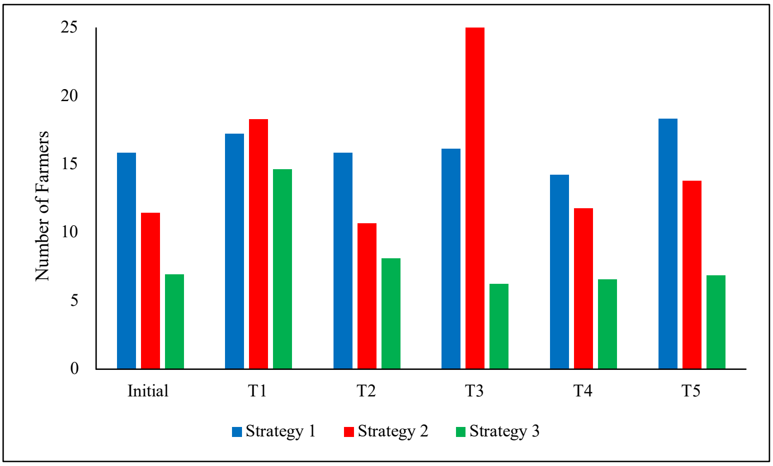
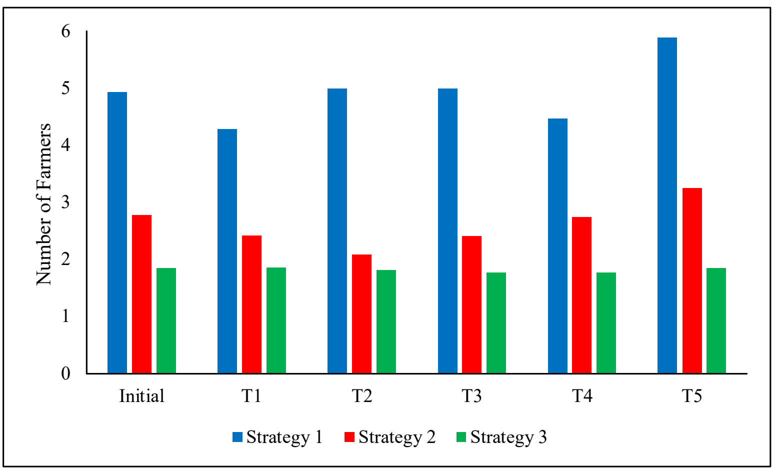


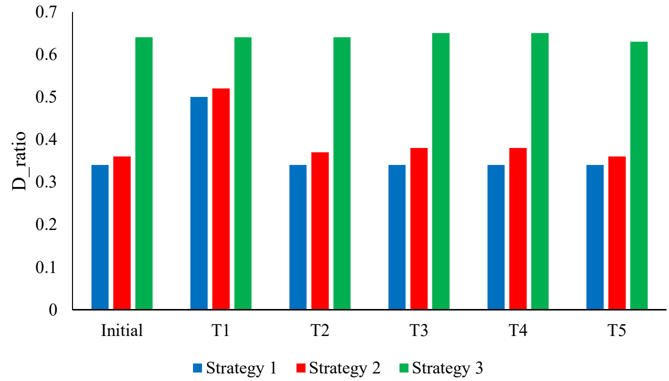
Figure 17 Defect analysis (see online version for colours)



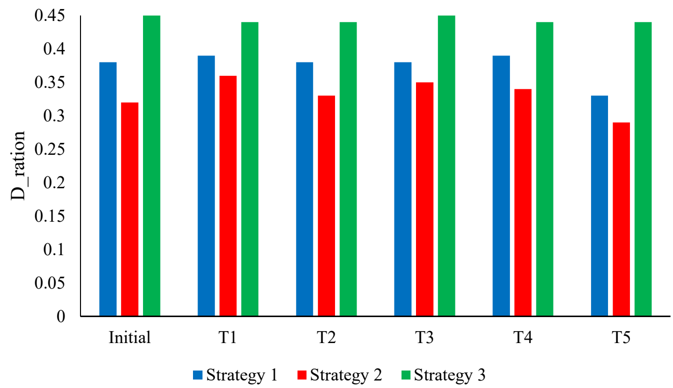
7.6 D_ratio

Figure 18 indicates that the D ratio of small-scale farmers is only affected by the transportation cost (*T*1). Small-scale farmers wish to sell most of their crops to distributors to reimburse them for expenses incurred due to increased transportation costs. The D_ratio of medium-any modification of performance parameters does not considerably influence scale farmers. However, very large-and large-scale farmers sell more to the distributor under strategies 2 and 3 (concerning the initial MAS) when the weight of farm size is decreased (in *T*2, $S = 0\%$ and *T*3, $S = 5\%$). Consequently, the 10% weight of the initial MAS significantly affects the reduction of volumes supplied by very large-and large-scale farmers.

Figure 18 D ratio analysis, (a) small sized farmers, (b) medium sized farmers, (c) large sized farmers, (d) very large sized farmers (see online version for colours)



(a)



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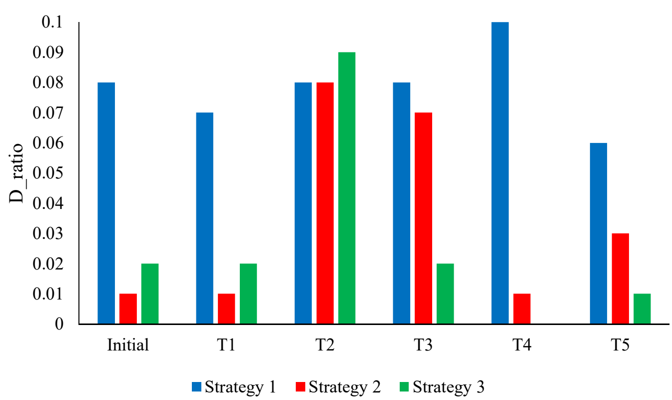
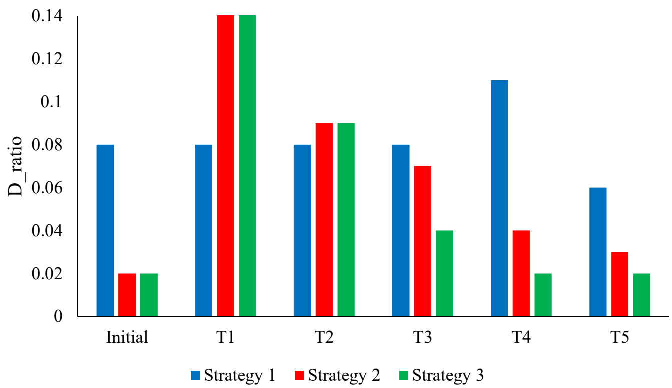


(c)

Figure 18 D ratio analysis, (a) small sized farmers, (b) medium sized farmers, (c) large sized farmers, (d) very large sized farmers (continued) (see online version for colours)

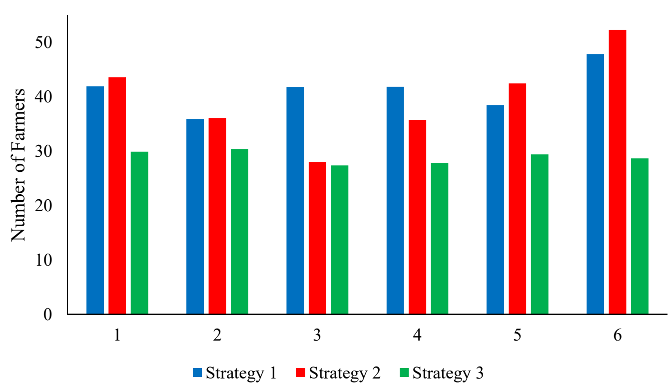


(d)

7.7 *Farm size distribution*

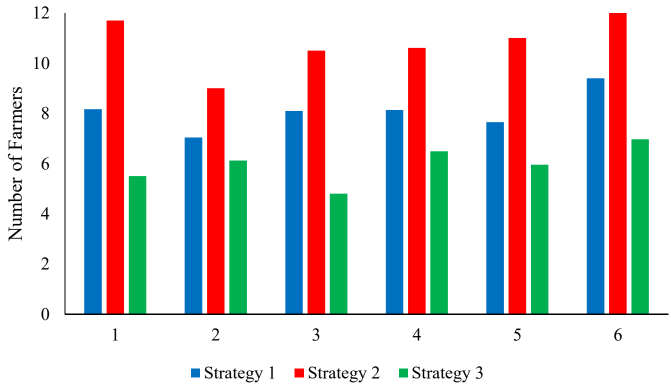
As shown in Figure 19, the strongest effects were observed regarding farm size distributions. The number of selected small-and medium-scale farmers is considerably affected by $T1$ (the increase in transportation costs creates a reduction in the number of small-and medium-scale farmers), while very large-and large-scale farmers are unaffected. For $T2$ and $T3$, the number of selected farmers (very large-and large-scale) is particularly central for strategies 2 and 3. For $T4$, the number of farmers selected decreases (statistically insignificant). For $T5$, the number of farmers selected under strategy 2 decreases (as the distributor requires more farmers to meet their demands, and increasing the number of selected farmers is crucial because of a low negotiation success rate).

Figure 19 Farmer distribution analysis, (a) small sized farmers, (b) medium sized farmers, (c) large sized farmers, (d) very large sized farmers (see online version for colours)



(a)

Figure 19 Farmer distribution analysis, (a) small sized farmers, (b) medium sized farmers, (c) large sized farmers, (d) very large sized farmers (continued) (see online version for colours)



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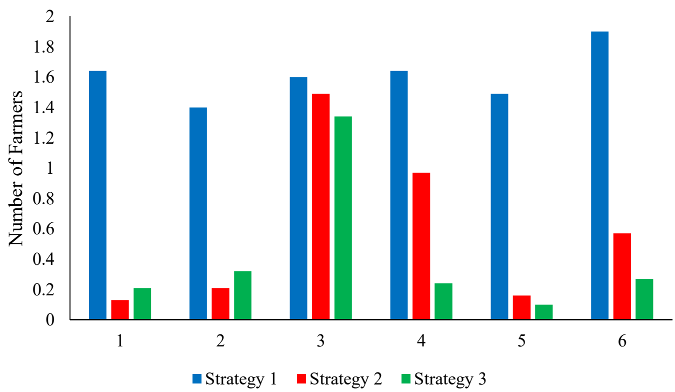

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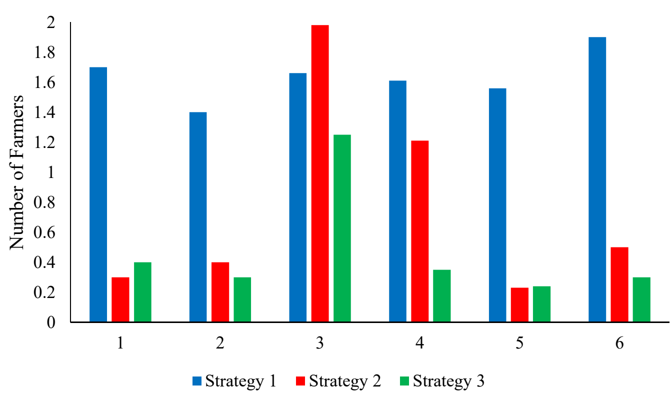

(d)

7.8 Contract length modification (applicable to strategy 3 only)

We increased the contract length to 30 (rather than 20) distribution cycles to determine its impacts on LFS metrics, and the sensitivity analysis shows an insignificant impact of contract length modifications on the LFS parameters.

Finally, our analysis of the three strategies shows that strategy 1 performs worse than strategies 2 and 3 though each strategy presents unique advantages. The simulation results show that the distributor must understand that initial investments in resources and time are essential to adequately help smallscale farmers meet performance constraints. Training them on ways to improve their performance is sometimes useful.

8 Conclusions

In this study, we developed an MAS of an abstract model of an LFS that involves a group of farmers operating at different scales who sell food and negotiate with a local distributor. The MAS is exploited to evaluate the performance metrics of the LFS better to understand the impacts of three distinct supplier selection strategies. The MAS is used to investigate this issue because the involved agents (farmers) are autonomous and heterogeneous (regarding goals, features, and behaviours). The MAS also assigns the distributor as a decision maker who uses a set of distinct metrics to assess farmer performance as the distributor does. The study results can help distributors develop supply chain management strategies to improve LFS profitability, efficiency, and sustainability.

We recommend examining how distributors or farmers may renege on a contract as an extension of our model. This problem was not investigated, even though it presents severe risks. In the proposed MAS, the distributor continues to purchase from a contracted farmer until a contract ends, even when they offer low-quality or imperfect food products. Furthermore, a contracted farmer sells the mentioned volume under a contract to the distributor in each distribution cycle, even when other buyers offer the farmer higher prices.

Finally, the study presents several significant contributions:

- It introduces an extended G-net model designed to support the modelling of classes and inheritance within object-oriented systems.
- The proposed methodology effectively incorporates inheritance mechanisms into the G-net formalism while maintaining the foundational Petri Net structure, facilitating design analysis and prototyping.
- The extended G-net model offers a more robust and expressive framework for capturing inheritance in concurrent systems by addressing the limitations of existing object-oriented Petri Net approaches.
- The study also investigates the inheritance anomaly, specifically, the challenge of synchronising inherited methods in concurrent object-oriented languages. It demonstrates how the extended model mitigates this issue through method refinement and implementing mutual exclusion strategies.

- A case study centred on a customer/vendor interaction is presented to illustrate the practical applicability of the model. This example demonstrates how G-nets can be used to formally model business processes and validate behavioural correctness and inheritance characteristics through reduction to conventional Petri Nets.

Declarations

All authors declare that they have no conflicts of interest.

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