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# Sustainable agriculture supply chain network design considering water-energy-food nexus using queuing system: A hybrid robust possibilistic programming

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**Abstract**

Due to the nature of the agricultural and food industry, the management of production, storage, transportation, waste disposal and environmental effects of their production, are of great importance. To deal with the sustainability issues linked to their supply chains, we propose in this study a mathematical model to design a sustainable supply chain of highly perishable agricultural product (strawberry). The model is a multiperiod, multiproduct multiobjective MINLP mathematical program that takes into consideration economic, social and environmental objectives to cover all aspects of sustainability. In addition, a G/M/S/M queuing system is developed for the transportation of harvested products between facilities for the first time. Since real-world problems related to industries such as food and agriculture are inherently uncertain, in this model, the important parameters of the problem are considered uncertain using fuzzy sets theory and a hybrid robust possibilistic programming model is developed. In addition, the Epsilon constraint approach converts the multiobjective mathematical model into a single-objective one and the Lagrangian relaxation method is used to effectively solve the model on a large scale. A case study in Iran is provided to investigate the results and discuss the solutions. Finally, a sensitivity analysis is performed to identify the impacts of important parameters on the solution. According to the analysis, equipping greenhouses with drip irrigation system and using solar panels in greenhouses, respectively, have the greatest impact on improving all target functions.

**Recommendations for Resource Managers**

- Multiobjective optimization shows trade-offs among conflicting objective function and assists decision-making to enhance sustainable agriculture industry.
- Focus on transportation system in fresh product will lead to less waste.
- The use of solar panels and drip irrigation helps to minimize water and energy consumption and $CO_2$ emission.

**KEYWORDS**

agriculture and foodhybrid robust possibilistic programmingmultiobjective optimizationqueuing systemsupply chain network designwater-food-energy nexus

## 1 | INTRODUCTION

Agricultural supply chains (ASCs) are nowadays under increasing pressure and the management of agri-food supply chains (AFSCs) has become much more challenging due to several reasons, including declining land sizes and growing demand, as well as due to the fact the world's population is expected to increase to more than 9 billion by 2050 (Sharma et al., 2018). The AFCS is a multilevel supply chain (SC) network consisting of primary production, production of semi-product by plants, production of finished products and distribution centers with multiple products like cereal, grains, fruits, and other vegetables (Fuchigami et al., 2019). The role of the ASC is to deliver agricultural products from farms to the consumer (Esteso et al., 2018). ASCs are one of the largest production sectors in Europe, with 4.25 million employees and 1 trillion dollars of financial turnover in the economy. Hence, it is required to develop effective and efficient models and methods to support the decision-making processes and develop the performance optimization of AFSCs (Amorim et al., 2015).

The quality of perishable products is affected significantly by ineffective supply chain management practices. Recent research shows that product losses are incurred during the product loading, shipment and unloading processes (Lipińska et al., 2019). This is because such practices may increase transportation and storage times, thereby influencing the "freshness" of products because of their perishability (Verdouw et al., 2010). Agri-food products expire on certain dates and experience continuous quality deterioration. Different types of these products may have different rates of deterioration as the number of utilized modes significantly affect lead time, waiting time, transportation time, as well as network configuration where the quality of products is influenced by travel time based on geographical location during transportation (Yakavenka et al., 2020). Accordingly, the freshness of a product is represented by transportation time and waiting time in the SC, thereby reducing postharvest losses (Manuel & Sowers, 2017). Thus, a robust network design guarantees that the optimization of transportation time and waiting time is of paramount importance throughout the SC. Strawberries are fruits that are mostly perishable in the SC due to their nature and improper management (Tuljak-Suban & Suban, 2015). Increasing processing line capacity, including storage facility, refrigerated warehouse, and transportation, as well as procurement in SCs, is also of paramount importance (Nunes et al., 2009). Considering the decline of client wait time at queue lines is a problem in the study of the SC network. Insufficient loading capacity necessitates time waiting in the queue, leading to environmental impacts and higher energy consumption (Parajuli et al., 2019). This SC entails transport fleets (responsible for transporting goods between different SC centers) to wait in the loading queue to receive services, thereby increasing wait and transport time between SC centers. This can be followed by an increased amount of waste and perishability in fresh products. Transport fleets are applied in loading systems with a finite-source M/G/S queuing system to make first-ever use of it in fresh product SCs. M/G/S stands for (M) exponentially distributed service time, (G) generally distributed entrance time, and (S) servers that provide services (Aziziankohan et al., 2017).

When solving a problem under real conditions, data of the optimization problem are not accurately known due to unavoidable errors in measurement, implementation, and estimation (Baghizadeh et al., 2021). The consideration of uncertainty in several parameters of the agriculture SC model can lead to a better representation of the real problem (Ben-Tal et al., 2005; Munhoz & Morabito, 2014). Since the inherent sources of uncertain parameters, such as demand, waiting time, water consumption and energy usage have a negative impact on the performance and robustness of AFSC, several authors (Hosseini-Motlagh et al., 2020) have mentioned the need for developing AFSC design models that consider the effect of existing resources of uncertainty. These challenges generate the need for management efficiency and the use of modern decision-making technology tools (Lucas & Chhajed, 2004)

The environmental impacts during the cultivation phase can be mainly attributed to the gas emissions of the diesel equipment, fertilizers, and land use change. Climate change, increasing global energy demand, and limited fossil fuel reserves have led to the use of clean and renewable energies, including solar thermal energy (STE), for sustainable agricultural production (Soto-Silva et al., 2017). Therefore, serious environmental issues have drawn the attention of the agricultural sector (Hosseini-Fashami et al., 2019).

There is a growing demand for the limited sources of water in parts of Europe and the Mediterranean Basin. So far, the largest quantities of water used in the value chain for fresh food and vegetables (FF&V) are attributed to crop cultivation (Cui et al., 2020). Available water for irrigation is mostly used by the conventional surface irrigation method, in which the water efficiency is very low, between 35% and 40% (Mekonnen & Hoekstra, 2011). Gustavsson and Stage (2011) claimed that some losses could reflect large amounts of water and energy consumption, accounting for almost 38% of all energy consumption in the food industry. In other words, energy consumption is the main expense in agricultural logistics (Gustavsson & Stage, 2011). Therefore, it is vital to study and analyze the causes and reduce its consumption.

Consequently, this paper mainly aims to explore an ASC in terms of sustainability, by taking into account major practical features overlooked in the related literature. This study seeks to answer the following questions:

- How can we develop a mathematical programming model to optimize perishable product SCs in the agricultural industry by taking into account the location-inventory-routing (LIR) problem under conditions of uncertainty?
- How to reduce energy and water consumption in the agricultural SC?
- How can the waiting and shipping time be minimized to prevent spoilage of harvested products?

Based on a large number of reviewed articles, it is indicated that there are some neglected hidden areas in the field of AFSC. To cover these gaps, this paper proposes a multiobjective multiperiod model of the SC of strawberry production. The objective functions of the model include maximizing the profit of selling strawberries including environmental cost, minimizing energy and water consumption and water waste, as well as a minimizing waiting time for harvested products transportation base on a G/M/S/M queue model. Moreover, reduction in environmental pollution and the use of fossil fuels are considered in first objective function as variable costs. These objective functions also minimize the waste of products indirectly. Applying solar panels to reduce pollution and energy consumption, along with equipping greenhouses with drip irrigation systems to minimize water waste and consumption, are among the implemented solutions of the model. Since the decay of agricultural products is a matter of great importance, adjustments are applied in the model to minimize the chance of its occurrence. One of the conditions that lead to waste and decay of products is waiting time, transportation time and the overproduction in relation to the capacity of warehouses in each period, where the excess production is decayed or discarded. To solve this problem, direct transportation is considered from greenhouses to distribution centers without packaging, which is also less expensive. The next factor that contributes to product decay is the environmental temperature changes during transportation, which is inevitable. Hence, products that decay in distribution centers or warehouses due to transportation are shipped to jam production factories at a lower price than the intact product.

As stated above, few articles have focused on uncertainty in the AFSC. Therefore, we consider fuzzy uncertainty in several prominent parameters of the problem, and solve it use the robust optimization method with the HRPP approach. A literature review indicates that mathematical approaches for solving models are often only suitable for small-scale problems. To cover this study gap, the ε-constraint approach is used to transform the four-objective model into a single-objective one. In addition, the Lagrangian relaxation (LR) method is applied to solve the model on a larger scale.

This study is the first to integrate all these features into agriculture SC, to the best of the knowledge of authors. Contributions of the present article can be summarized as follows:

- Designing a four-objective model with a water-food-energy approach.
- Considering G/M/S//M queuing system for minimizing waiting and transportation time for first time in agriculture SC.
- Investigation of solar panels performance to provide the required energy and reduce the environmental pollution of greenhouses.
- Investigation of drip irrigation systems effect on water consumption and costs.
- Applying direct product transportation lines to distribution centers to decrease the waste and disposal of produced strawberries due to inadequate warehouse capacity.
- Indirect measurement of water waste with regard to the waste of each produced strawberry unit.
- Classifying produced strawberries in two groups of organic and inorganic as well as providing them to customers in two forms: packaged and unpackaged.
- Considering the destructive impacts of using fertilizers as environmental effect.

## 2 | PROBLEM STATEMENT

An AFSC network design combines various activities, including facility location, inventory management, production scheduling, and transportation. Such activities entail making some decisions, including strategic decisions, such as facility size/location determination in an SC, tactical decisions, such as inventory replenishment time determination, and operational decisions, such as resultant route determination to transport products to final destinations, planning levels, and execution. There are also some suggested solutions to minimize the waste and disposal of products. In this model, strawberry products will be cultivated and produced by two organic and inorganic methods. Based on Figure 1, which shows the suggested agricultural SC, greenhouses send organic and inorganic strawberries to warehouses for packaging and to provide an appropriate temperature to prevent decay. After packaging, the products are sent to distribution centers and subsequently to customer zones to meet the existing demands. Since the decay of food and agricultural products is of great importance, actions are taken in the model to address this issue. Excessive production is among the issues that result in the decay of

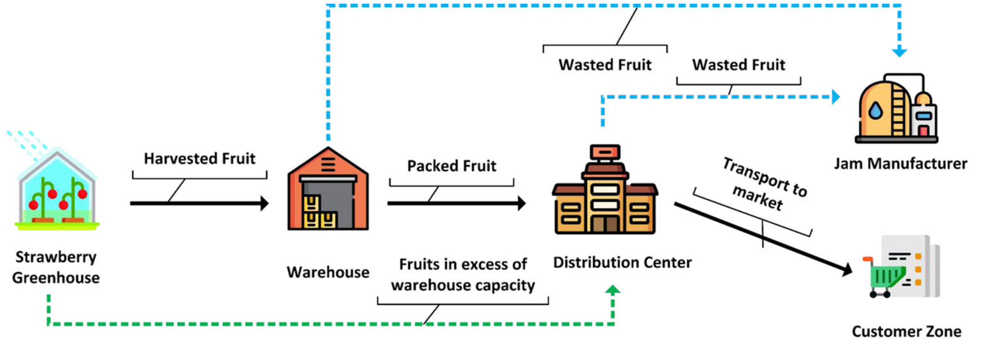


FIGURE 1 Suggested supply chain network for strawberry production

products, as the decayed products are disposed of. To tackle this issue, the products are directly transported to distribution centers without packaging. Unavoidable environmental temperature changes during the transportation are another factor that is also taken into account; therefore, the products, which are decayed as a result of transportation in distribution centers or storage, are shipped to jam production factories as raw materials at a cheaper price.

The assumptions of the suggested model are as follows:

- Organic and inorganic strawberries are cultivated without and with fertilizers, respectively.
- The selling price of organic strawberries is higher than the inorganic products.
- The decay rate of organic strawberries is higher than inorganic ones.
- The decay rate of strawberries is insignificant after the packaging process in warehouses.
- Greenhouse products that are in excess of warehouse capacity are sent to distribution centers and customer zones for sale without being packaged.
- There is no limitation in the volume of decayed products that are sent to jam factories.
- Factories only buy decayed products; therefore, strawberries in excess of the capacity of distribution centers are disposed of.
- Because of the short distance and transportation time between the greenhouse and the warehouse, the decay rate resulting from temperature changes is negligible.

## 2.1 | G/M/S//M queue theory

As mentioned earlier, in this study, a queuing system is used to minimize the waiting time for harvested fruits between the greenhouses and the warehouses/distribution centers. Therefore, based on Mohtashami et al. (2020) research on G/M/S queue theory with finite source in each part of SC, a G/M/S//M queuing system has been considered in each loading system (greenhouses). The number of transport fleets between loading and unloading centers (distribution centers and warehouses), serving as the queuing system customers, is designated by number of transportation fleet between centers (NV). The critical role of each transport fleet in each of the loading centers is to carry items from one part to another and then return upon unloading. Hence, the return time of vehicles includes the time required to reach the destination, the unloading time and the time required to return to the origin. Unloading times in distribution centers and warehouses are assumed to be generally distributed with a mean of $1/\mu'$. Furthermore, the time spent for transporting from center $i$ to center $j$ for unloading at center $j$, and finally return to center $i$ has also been assumed to be generally distributed with an average of $1/T_{ij}$ and $1/T_{ji}$, respectively. Thus, the time spent for transporting from center $i$ to center $j$ and finally return to center $i$ upon unloading can be measured using the following equation:

$$\frac{1}{\lambda_i} = \frac{1}{\frac{1}{T_{ij}} + \frac{1}{T_{ji}} + \frac{1}{\mu'}}. \tag{1}$$

There is the same limiting probability for M/M/C//M and G/M/C//M queuing systems in terms of the number of customers in a system, provided that customers or vehicles are not dependent on the source. It merely depends on the average time spent by the customer on the source once the specified service is received. $C$ is the number of servers considering these queuing systems primarily in maintenance systems, while $M$ is the number of machines getting maintenance services. Here, $1/\lambda$ stands for the average time spent by a machine on the source or running upon getting service. Herein, the time elapsed between departure and arrival at a center is equal to the time spent by customers on the source in the maintenance model above. Equation (1) is applied to calculate the average time spent on transporting to unloading center and then return. The loading system proposed in this study is evidently comparable to a finite-source maintenance model in which $1/\lambda$ is determined by Equation (1). A sufficient number of servers have been assumed in unloading centers without any queue, given the assumption that transport fleets are independent of applying M/M/C//M formula for G/M/C//M queuing systems. Thus, transport fleets first go to unloading centers and once unloaded, they came back to loading centers. Additionally, based on the results of Little for a finite-source G/M/S queuing system, Equation (2) is true, then Equation (3) is shown as follows:

$$Z_i(x) = Z(x), \quad i = 1, \ldots, M, \tag{2}$$

$$\lambda(M - L)W = L. \tag{3}$$

In Equation (2), $Z_i(x)$ represents the distribution function of time spent by the customer or machine $i$ on the source. Hence, this study considers all transport fleets and servers in unloading centers to be the same. This study assumes requirements for departure and return of transport fleets to be the same. Equation (2) is used to determine the time spent by each transport fleet on the source, which is equivalent to the time spent for transit, unloading, and returning. A comparison was made between Equation (3) and Equation (4) to demonstrate that $\bar{\lambda}$ has been measure using Equation (5) in a G/M/S//M.

$$L = \bar{\lambda} W, \tag{4}$$

$$\bar{\lambda} = (M - L)\lambda. \tag{5}$$

## 2.2 | Mathematical model

Before explaining the proposed model, the sets, parameters and decision variables will be introduced in order.

| **Sets** | **Definition** |
|---|---|
| $F$ | greenhouses |
| $w$ | warehouses |
| $S$ | Ddistribution centers |
| $J$ | jam factories (producers) |
| $t$ | period time |
| $d$ | demand zone |

| Parameter | Description |
|---|---|
| $SF_f$ | the area of greenhouse $F$ under cultivation |
| $CD$ | the total allocated governmental fund to equip the greenhouses with drip irrigation system |
| $PD$ | the total allocated governmental fund to equip the greenhouses with solar panels |
| $RF_f$ | production volume of inorganic strawberry per square meter of greenhouse $F$ (kg) |
| $RN_f$ | production volume of organic strawberry per square meter of greenhouse $F$ (kg) |
| $Mins$ | the minimum required strawberry production in return for receiving drip irrigation system (kg) |
| $CF$ | the cost of equipping each area of greenhouses with drip irrigation system |
| $PF$ | the cost of equipping each area of greenhouses with solar panels |
| $CC$ | the cost of harvesting each strawberry unit in the greenhouses |
| $DS$ | the distance between two facilities (km) |
| $PN$ | the decay rate of organic strawberries in transportation per each unit of distance |
| $PF$ | the decay rate of inorganic strawberries in transportation per each unit of distance |
| $DF_{dt}$ | the amount of demand for inorganic strawberry in area $d$ in the period of $t$ |
| $DN_{dt}$ | the amount of demand for organic strawberry in area $d$ in the period of $t$ |
| $VF$ | the price of each unit of packaged inorganic strawberry |
| $Vb$ | the price of each unit of unpackaged inorganic strawberry |
| $Vd$ | the price of each unit of packaged organic strawberry |
| $Vs$ | the price of each unit of unpackaged organic strawberry |
| $Vk$ | the selling price of each decayed strawberry unit to jam production factories |
| $NC_s$ | the cost of each capacity unit of distribution center $s$ for collecting and distributing each strawberry unit (kg) |
| $CPD_s$ | the maximum budget in each period to provide the capacity required by distribution centers $s$ |
| $FR$ | the required fertilizer per each ($m^2$) of greenhouse area to produce inorganic strawberry |
| $FC$ | the cost of each unit of the fertilizer |
| $ICR$ | the cost of irrigating each square meter of a greenhouse by drip irrigation method |
| $TCR$ | the cost of irrigating each square meter of a greenhouse by traditional irrigation method |
| $CP_w$ | capacity of warehouse $w$ |
| $WC$ | water consumption per square meter of a greenhouse equipped with drip irrigation system |
| $WT$ | water consumption per square meter of a greenhouse equipped with traditional irrigation system |
| $CE$ | the cost of each unit of consumed fuel in greenhouses without solar panels |
| $Fu$ | the amount of fuel required per square meter of greenhouse area to provide adequate temperature |
| $PC$ | the cost of packaging for each strawberry unit |

| Parameter | Description |
|---|---|
| $OC_w$ | the operation costs of warehouse management in warehouse *W* |
| $EC_w$ | the establishment cost of warehouse *W* with the capacity of $cp_w$ |
| *HC* | the preservation cost of each unit (kg) of inventory in warehouse centers |
| *CN* | the costs of providing capacity in distribution center s per each strawberry unit |
| $OC_s$ | the operation costs of distribution center *s* per (kg) strawberry |
| *TR* | percent of perishability of products in transportation system |
| $TRP_{fw}$ | the transportation costs of each strawberry unit from greenhouse *F* to warehouse *W* |
| $TRP_{fs}$ | the transportation costs of each strawberry unit from greenhouse F to distribution center *s* |
| $TRP_{ws}$ | the transportation costs of each strawberry unit from warehouse *W* to distribution center *s* |
| $TRP_{sj}$ | the transportation costs of each decayed strawberry unit from distribution center *s* to factory *j* |
| $TRP_{wj}$ | the transportation costs of each decayed strawberry unit from warehouse *W* to factory *j* |
| $TRP_{sd}$ | the transportation cost of each strawberry unit from distribution center *s* to customer zone *d* |
| *CRW* | the amount of water required per unit of strawberry in greenhouses equipped with drip irrigation system |
| *CNW* | the amount of water required per unit of strawberry in greenhouses equipped with traditional irrigation system |
| *WW* | the amount of indirect water loss by each perished strawberry unit in the distribution center |
| *JC* | the amount of energy required to irrigate each unit of strawberry (kg) in greenhouse equipped with drip irrigation systems |
| *Jb* | the amount of energy required to irrigate each unit of strawberry (kg) in greenhouse equipped with traditional irrigation systems |
| *Jd* | the amount of required energy generated by fossil fuel to provide the adequate temperature for each unit of strawberry in greenhouses without solar panels |
| *Jr* | the amount of required energy generated by solar panels to provide the adequate temperature for each unit of strawberry in greenhouses equipped with solar panels |
| *CE* | the amount of produced $CO_2$ by the transportation between facilities per strawberry unit (kg) |
| $EF_t$ | the amount of produced $CO_2$ by irrigating each square meter of the area of greenhouses with drip irrigation systems in each period *t* |
| $EN_t$ | the amount of produced $CO_2$ by irrigating each square meter of the area of greenhouses with traditional irrigation systems in each period *t* |
| $ER_t$ | the amount of produced $CO_2$ by providing adequate temperature for each unit of area of greenhouses powered by fossil fuel in each period *t* |
| *CV* | capacity of each vehicle (kg) |
| *Tx* | tax on per unit $CO_2$ emission |
| $K_{fw}$ | number of servers in greenhouse *F* for loading and then transferring products to warehouse *W* |

(Continues)

| Parameter | Description |
|---|---|
| $K_{fs}$ | number of servers in greenhouse $F$ for loading and then transferring products to distribution center $S$ |
| $NV_{fw}$ | number of transportation fleets between greenhouse $F$ and warehouse $W$ |
| $NV_{fs}$ | number of transportation fleets between greenhouse $F$ and distribution center |
| $Tfw$ | total average time for transferring from greenhouse $F$ to warehouse $W$ and returning |
| $Tfs$ | total average time for transferring from greenhouse $F$ to distribution center $S$ and returning |

| Variables | Description |
|---|---|
| $dt_f$ | 1, if the greenhouse is equipped with a drip irrigation system; otherwise, 0 |
| $pv_f$ | 1, if the greenhouse is equipped with a solar panel; otherwise, 0 |
| $QF_{fwt}$ | the quantity of produced inorganic strawberry in greenhouse $F$ that is sent to warehouses in the period of $f$ |
| $QN_{fwt}$ | the quantity of produced organic strawberry in greenhouse $F$ that is sent to warehouses in the period of $f$ |
| $FTR_f$ | 1, if greenhouse $f$ has inorganic productions; otherwise, 0 |
| $QR_{fst}$ | the quantity of inorganic strawberry in excess of warehouse capacity that is sent directly from greenhouse $f$ to distribution center $s$ in the period of $t$ (unpackaged) |
| $QD_{wst}$ | the quantity of packaged inorganic strawberry that is sent from warehouses to distribution center $s$ in the period of $t$ |
| $QC_{wst}$ | the quantity of packaged organic strawberry that is sent from warehouses to distribution center $s$ in the period of $t$ |
| $QA_{fst}$ | the quantity of organic strawberry in excess of warehouse capacity that is sent directly from greenhouse $f$ to distribution center $s$ in the period of $t$ (unpackaged) |
| $QE_{sdt}$ | the quantity of inorganic strawberry ships from distribution center $s$ to demand zone d in the period of $t$ (unpackaged) |
| $QZ_{sdt}$ | the quantity of organic strawberry ships from distribution center $s$ to demand zone d in the period of $t$ (unpackaged) |
| $QG_{sdt}$ | the quantity of inorganic strawberry ships from distribution center $s$ to demand zone d in the period of $t$ (packaged) |
| $QH_{sdt}$ | the quantity of organic strawberry ships from distribution center $s$ to demand zone d in the period of $t$ (packaged) |
| $PC_{st}$ | the capacity of distribution center $s$ for inorganic products in the period of $t$ |
| $KC_{st}$ | the capacity of distribution center $s$ for organic products in the period of $t$ |
| $QM_{sjt}$ | the quantity of decayed inorganic strawberry in distribution center $s$ that is sent to factory $j$ in the period of $t$ |

| Variables | Description |
|---|---|
| $QK_{wjt}$ | the quantity of decayed organic strawberry in warehouse $W$ that is sent to factory $j$ in the period of $t$ |
| $Z_w$ | 1, if the warehouse $W$ is established; otherwise, 0 |
| $QP_{ft}$ | the quantity of produced inorganic strawberry in greenhouse $F$ in the period of $t$ |
| $QS_{ft}$ | the quantity of produced organic strawberry in greenhouse $F$ in the period of $t$ |
| $IF_{wt}$ | the quantity of inorganic strawberry supply in warehouse $W$ in the period of $t$ |
| $IS_{wt}$ | the quantity of organic strawberry supply in warehouse $W$ in the period of $t$ |
| $LO_{st}$ | the quantity of inorganic strawberry that is disposed of in distribution center $s$ in the period of $t$ |
| $LN_{st}$ | the quantity of organic strawberry that is disposed of in distribution center $s$ in the period of $t$ |
| $\mu_{fw}$ | loading rate in greenhouse $F$ for transferring to warehouse W |
| $\mu_{fs}$ | loading rate in greenhouse $F$ for transferring to distribution center $S$ |
| $\lambda_{fw}$ | average time for a vehicle for returning to greenhouse $F$ after departure from greenhouse $F$ for going to warehouse $W$ in loading system |
| $\lambda_{fs}$ | average time for a vehicle for returning to greenhouse $F$ after departure from greenhouse $F$ for going to distribution center $S$ in loading system |
| $W_{fw}$ | average waiting time for loading in greenhouse $F$ and the transferring products to warehouse $W$ |
| $W_{fs}$ | average waiting time for loading in greenhouse $F$ and the transferring products to distribution center |
| $\mu'_w$ | unloading rate in warehouse $W$ |
| $\mu'_s$ | unloading rate in distribution center $S$ |
| $\mathrm{L_{fw}}$ | average number of transportation vehicles for loading in greenhouse $F$ for transferring to warehouse $W$ |
| $\mathrm{L_{fs}}$ | average number of transportation vehicles for loading in greenhouse $F$ for transferring to greenhouse $S$ |
| $\mathrm{LQ_{fw}}$ | aaverage length of queue for loading in greenhouse $F$ for transferring to warehouse $W$ |
| $\mathrm{LQ_{fs}}$ | average length of queue for loading in greenhouse $F$ for transferring to distribution center $S$ |
| $\pi^0_{fw}$ | idle probability of server for loading in greenhouse $F$ for transferring products to warehouse $W$ |
| $\pi^0_{fs}$ | idle probability of server for loading in greenhouse $F$ for transferring products to distribution center $S$ |
| $\pi^n_{fw}$ | Probability of existing n machine for loading in greenhouse $F$ for transferring products to warehouse $W$ |
| $\pi^n_{fs}$ | probability of existing $n$ machine for loading in greenhouse $F$ for transferring products to distribution center $S$ |

### 2.2.1 | Objective functions

The suggested model is a MINLP multiobjective and multiperiod, which consists of four objective functions as follows:

$$\begin{aligned}
\text{Max}\, M_1 = &\sum_s \sum_d \sum_t QG_{sdt} \times vc + \sum_s \sum_d \sum_t QE_{sdt} \times vf + \sum_s \sum_d \sum_t QH_{sdt} \times vb \\
&+ \sum_s \sum_d \sum_t QZ_{sdt} \times vs + \left[\sum_s \sum_j \sum_t QM_{sjt} + \sum_w \sum_j \sum_t QK_{wjt}\right] \times VK \\
&+ \left[\sum_f \sum_t QS_{ft} + \sum_j \sum_t QP_{ft}\right] \times CC + \sum_f SF_f \times FTR_f \times FR \times FC \\
&- \sum_f SF_f \times dt_f \times ICR \times WC - \sum_f SF_f \times (1 - dt_f) \times TCR \times Wt \\
&- \sum_f SF_f \times (1 - PV_f) \times CE - \left[\sum_f \sum_w \sum_t QF_{fwt} + \sum_f \sum_w \sum_t QN_{fwt}\right] \\
&\times (PCS + OC_w) - \sum_w Z_w \times EC_w - \left[\sum_w \sum_t I(F_{wt} + IS_{wt})\right] \times HC \\
&- \left[\sum_s \sum_t PC_{st} + \sum_s \sum_t KC_{st}\right] \times CN - \sum_w \sum_s \sum_t (QD_{wst} + QC_{wst}) \times OC_s \\
&- \sum_f \sum_s \sum_t (QR_{fst} + QA_{fst}) \times OC - \sum_f \sum_w \sum_t QF_{fwt} \times TRP_{fw} \\
&- \sum_f \sum_w \sum_t QN_{fwt} \times TRP_{fw} - \sum_f \sum_s \sum_t QR_{fst} \times TRP_{fs} \\
&- \sum_f \sum_s \sum_t QA_{fst} \times TRP_{fs} - \sum_s \sum_j \sum_t QM_{sjt} \times TRP_{sj} - \sum_w \sum_j \sum_t QK_{wjt} \times TRP_{wj} \\
&- \sum_s \sum_d \sum_t QH_{sdt} \times TRP_{sd} - \sum_s \sum_d \sum_t QZ_{sdt} \times TRP_{sd} \\
&- \sum_s \sum_d \sum_t QG_{sdt} \times TRP_{sd} - \sum_s \sum_d \sum_t QE_{sdt} \times TRP_{sd} \\
&- \sum_f \sum_t SF_f \times dt_f \times EF_t - \sum_f \sum_t SF_f \times (1 - dt_f) \times EN_t \\
&- \sum_f \sum_t SF_f \times (1 - PV_f) \times ER_t - \sum_f \sum_w \sum_t QF_{fwt} \times DS_{fw} \times CE \\
&- Tx \times \left[\sum_f \sum_w \sum_t QN_{fwt} \times DS_{fw} \times CE + \sum_f \sum_s \sum_t QR_{fst} \times DS_{fs} \times CE\right. \\
&+ \sum_f \sum_s \sum_t QA_{fst} \times DS_{fs} \times CE + \sum_w \sum_s \sum_t QD_{wst} \times DS_{ws} \times CE \\
&+ \sum_w \sum_s \sum_t QC_{wst} \times DS_{es} \times CE + \sum_s \sum_j \sum_t QM_{sjt} \times DS_{sj} \times CE \\
&+ \sum_w \sum_j \sum_t QK_{wjt} \times DS_{wj} + \sum_s \sum_d \sum_t QH_{sdt} \times DS_{sd} \times CE \\
&\left.+ \sum_s \sum_d \sum_t QZ_{sdt} \times DS_{sd} \times CE + \sum_s \sum_d \sum_t QG_{sdt} \times DS_{sd} \times CE\right],
\end{aligned} \tag{6}$$

$$\begin{aligned}
\text{Min}\, M_2 = &\sum_f \sum_t [QS_{ft} + QP_{ft}] \times dt_f \times CRW + \sum_f \sum_t [QS_{ft} + QP_{ft}] \times (1 - dt_f) \\
&\times CNW + \sum_s \sum_t LO_{st} \times ww + \sum_s \sum_t LN_{st} \times ww,
\end{aligned} \tag{7}$$

$$\begin{aligned}
\text{Min}\, M_3 = &\sum_f \sum_t [QS_{ft} + QP_{ft}] \times dt_f \times Jc + \sum_f \sum_t [QS_{ft} + QP_{ft}] \times (1 - dt_f) \times Jb \\
&+ \sum_f \sum_t [QS_{ft} + QP_{ft}] \times PV_f \times Jr + \sum_f \sum_t [QS_{ft} + QP_{ft}] \times (1 - PV_f) \times Jd,
\end{aligned} \tag{8}$$

$$\begin{aligned}
\min Z_4 = &\sum_f \sum_w \sum_t (NV_{fwt} - L_{fwt})\lambda_{fwt} + \sum_f \sum_s \sum_t (NV_{fst} - L_{fst})\lambda_{fst} \sum_f \sum_s \sum_t W_{fst} \\
&\times LQ_{fst} + \sum_f \sum_w \sum_t W_{fwt} \times LQ_{fwt}.
\end{aligned} \tag{9}$$

The first objective function is for profit maximization from the sale of products. In this equation, the costs of harvesting, irrigation, energy, and transportation along with facility supplies and operation costs are subtracted from the profit earned by the selling strawberries to maximize the profits. Moreover, the tax on carbon dioxide, formulated in the last part of the first objective function, attempts to minimize the environmental effects. The second objective function tries to minimize water consumption by minimizing disposals and specifying the type of irrigation system. The third objective function minimizes the energy consumption of strawberry cultivation by considering two factors such as providing the appropriate temperature for greenhouses and providing the required energy for irrigation systems. Eventually, the final objective function attempt to reduce harvested production waiting and transportation time from greenhouses to distribution centers/warehouses.

### 2.2.2 | Constraints

$$\sum_f SF_f \times dt_f \times CF \leq CD, \tag{10}$$

$$\sum_f SF_f \times PV_f \times PF \leq PD, \tag{11}$$

$$QP_{ft} \leq SF_f \times RF_f \times FTR_f \quad \forall\ F, t, \tag{12}$$

$$QS_{ft} \leq SF_f \times RN_f \times (1 - FTR_f) \quad \forall\ F, t, \tag{13}$$

$$QP_{ft} \geq Mins \times dt_f \times SF_f \times RF_f \quad \forall\ F, t, \tag{14}$$

$$QS_{ft} \geq Mins \times dt_f \times SF_f \times NF_f \quad \forall\ F, t, \tag{15}$$

$$\sum_f QF_{fwt} \times [1 - (PF \times DS_{fw})] - \sum_s QD_{wst} + IF_{\mathrm{w,t-1}} = IF_{w,t} \quad \forall\ w, t, \tag{16}$$

$$\sum_f QN_{fwt} \times [1 - (PN \times DS_{fw})] - \sum_s QC_{wst} + Is_{w,t-1} = IS_{w,t} \quad \forall\ w, t, \tag{17}$$

$$IF_{fw} + IS_{wt} \leq CP_w \times Z_w \quad \forall\ w, t, \tag{18}$$

$$QP_{ft} = \sum_w QF_{fwt} + \sum_s QR_{fst} + LO_{ft} \quad \forall\ f, t, \tag{19}$$

$$QS_{ft} = \sum_w QN_{fwt} + \sum_s QA_{fst} + LN_{ft} \quad \forall\ f, t, \tag{20}$$

$$\sum_w QD_{wst} + \sum_f QR_{fst} \times [1 - (PF + Tr) \times DS_{fs}] \leq PC_{st} \quad \forall\ s, t, \tag{21}$$

$$\sum_w QC_{wst} + \sum_f QA_{fst} \times [1 - (PN + Tr) \times DS_{fs}] \leq KC_{st} \quad \forall\ s, t, \tag{22}$$

$$\sum_w QC_{wst} \times [(PN + tr) \times DS_{ws}] + \sum_f QA_{fst} \times [(PN + Tr) \times DS_{fs} = \sum_j QM_{sjt} \quad \forall\ s, t, \tag{23}$$

$$\sum_f QF_{fwt} \times (PF \times DS_{fw}) + \sum_f QN_{fwt} \times [(PF \times DS_{fw}) = \sum_j QK_{wjt} \quad \forall\ w, t, \tag{24}$$

$$\sum_f QF_{fwt} \leq cap_w \times Z_w \quad \forall\ t, w, \tag{25}$$

$$\sum_f QN_{fwt} \leq cap_w \times Z_w \quad \forall\ t, w, \tag{26}$$

$$\sum_f QR_{fst} \times [1 - (PR + TR) \times DS_{fs}] = \sum_d QE_{sdt} \quad \forall\ t, s, \tag{27}$$

$$\sum_f QA_{fst} \times [1 - (PN + TR) \times DS_{fs}] = \sum_d QZ_{sdt} \quad \forall\ t, s, \tag{28}$$

$$\sum_w QD_{Wst} = \sum_d QG_{sdt} \quad \forall\ s, t, \tag{29}$$

$$\sum_d QH_{sdt} = \sum_w QC_{wst} \quad \forall\ s, t, \tag{30}$$

$$\sum_s QG_{sdt} + \sum_s QE_{sdt}\,[1 - (PR + TR) \times DS_{fs}] \geq DF_{dt} \quad \forall\ t, d, \tag{31}$$

$$\sum_s QH_{sdt} + \sum_s QZ_{sdt}\,[1 - (PR + TR) \times DS_{fs}] \geq DN_{dt} \quad \forall\ t, d, \tag{32}$$

$$(NV_{fst} - L_{fst})\lambda_{fst} \times cv \leq QR_{fst} + QA_{fst}, \tag{33}$$

$$(NV_{fwt} - L_{fwt})\lambda_{fwt} \times cv \leq QR_{fwt} + QN_{fwt} \quad \forall\ f, w, t, \tag{34}$$

$$\pi^{\circ}_{fwt} = \left[1 + \sum_{n=1}^{k_{fwt}-1} \left(\frac{\lambda_{fwt}}{\mu_{fwt}}\right)^n + \sum_{n=k_{fwt}}^{NV_{fwt}} \left(\frac{n!}{k_{fwt}^{\,n-k_{fwt}} \times k_{fwt}!}\right)\left(\frac{\lambda_{fwt}}{\mu_{fwt}}\right)^n\right]^{-1} \quad \forall\ f, w, t, \tag{35}$$

$$\pi^{\circ}_{fst} = \left[1 + \sum_{n=1}^{k_{fst}-1} \left(\frac{\lambda_{fst}}{\mu_{fst}}\right)^n + \sum_{n=k_{fst}}^{NV_{fst}} \left(\frac{n!}{k_{fst}^{\,n-k_{fst}} \times k_{fst}!}\right)\left(\frac{\lambda_{fst}}{\mu_{fst}}\right)^n\right]^{-1} \quad \forall\ f, s, t, \tag{36}$$

$$\pi^{n}_{fwt} = \begin{cases} \left(\dfrac{\lambda_{fwt}}{\mu_{fwt}}\right)^n \pi^{\circ}_{fwt}, & 0 \leq n \leq k_{fwt} \\ \left(\dfrac{n!}{k_{fwt}^{\,n-k_{fwt}} \times k_{fwt}!}\right) \times \left(\dfrac{\lambda_{fwt}}{\mu_{fwt}}\right)^n \pi^{\circ}_{fwt}, & k_{fwt} \leq n \leq NV_{fwt} \end{cases} \quad \forall\ f, w, t, \tag{37}$$

$$\pi^{n}_{fst} = \begin{cases} \left(\dfrac{\lambda_{fst}}{\mu_{fst}}\right)^n \pi^{\circ}_{fst}, & 0 \leq n \leq k_{fst} \\ \left(\dfrac{n!}{k_{fst}^{\,n-k_{fst}} \times k_{fst}!}\right) \times \left(\dfrac{\lambda_{fst}}{\mu_{fst}}\right)^n \pi^{\circ}_{fst}, & k_{fst} \leq n \leq NV_{fst} \end{cases} \quad \forall\ f, s, t, \tag{38}$$

$$L_{fwt} = \sum_{n=0}^{NV_{fwt}} n\pi^{n}_{fwt} \quad \forall\ f, w, t, \tag{39}$$

$$L_{fst} = \sum_{n=0}^{NV_{fst}} n\pi^{n}_{fst} \quad \forall\ f, w, t, \tag{40}$$

$$B_{fwt} = \frac{L_{fwt}}{(NV_{fwt} - L_{fwt})\lambda_{fwt}} \quad \forall\ f, s, t, \tag{41}$$

$$B_{fst} = \frac{L_{fst}}{(NV_{fst} - L_{fst})\lambda_{fst}} \quad \forall\ f, w, t, \tag{42}$$

$$LQ_{fwt} = \sum_{n=1}^{NV_{fwt}} (n - k_{fwt})\pi^{n}_{fwt} \quad \forall\ f, s, t, \tag{43}$$

$$LQ_{fst} = \sum_{n=1}^{NV_{fst}} (n - k_{fst})\pi_{fst}^{n} \quad \forall f, w, t, \tag{44}$$

$$\lambda_{fwt} = \frac{1}{\frac{1}{T_{fw}} + \frac{1}{T_{wf}} + \frac{1}{\mu'_{wt}}} \quad \forall f, s, t, \tag{45}$$

$$\lambda_{fst} = \frac{1}{\frac{1}{T_{fs}} + \frac{1}{T_{sf}} + \frac{1}{\mu'_{st}}} \quad \forall f, s, t. \tag{46}$$

The constraints (10) and (11) determine the maximum available governmental budget to equip the greenhouses with drip irrigation systems and solar panels. Constraint (12) specifies the maximum cultivation efficiency of inorganic products (with fertilizers). Constraint (13) determines the maximum amount of organic strawberry production (without fertilizers). Constraints (14) and (15) determine the minimum required strawberry production in return for receiving government funds to provide the greenhouses with drip irrigation systems. Equations (16) and (17) indicate the amount of organic and inorganic strawberry supplies in warehouses at each period. Constraint (18) guarantees that the amount of supply does not exceed the maximum permitted quantity in each period in warehouses after their establishment. Constraints (19) and (20) confirms that the amount of produced organic and inorganic strawberries in each period and each greenhouse is equal to the amount of strawberry shipped to the warehouses and distribution centers and waste. Constraints (21) and (22) ensure that the strawberries shipped to distribution centers from greenhouses and warehouses are stored as per the capacity of distribution centers and the excess is disposed of. Constraint (23) identifies the amount of strawberries that are decayed due to temperature changes and transportation from distribution centers to jam production factories. Constraint (24) identifies the amount of strawberries that are decayed due to transportation from the warehouses to jam production factories. Constraint (25) and (26) ensures that the transportation of products from greenhouses to warehouses depends on the establishment of the specific warehouse. Constraints (27) and (28) determine the amount of unpackaged organic and inorganic strawberries that are in the customer zone to supply the demand. Constraints (29) and (30) ensure that the amount of packaged organic and inorganic strawberries sent to customer zones from the distribution centers is equal to the amount shipped from warehouses to distribution centers. Constraint (31) ensures that the total of packaged and unpackaged inorganic strawberries satisfies the demand. Constraint (32) ensures that the total of packaged and unpackaged organic strawberries satisfies the demand. As Constraints (33) and (34) showed, the flows from the greenhouses to the warehouses/distribution center must be below the total production in each period. Moreover, the probability of product transfer to warehouses/distribution centers by the greenhouses can be measured using Constraint (35) and Constraint (36). Constraints (37) and (38) estimate the possibility of current servers in the greenhouses of the SC. Constraints (39) and (40) can be used to calculate the average number of consumers in the system in various centers. Constraints (41) and (42) and Constraints (43) and (44) calculate average wait time in each of the centers, and average wait time in queue, respectively. Constraints (45) and (46) calculates the average time spent by a certain between departure and arrival at a center in the loading system.

# 3 | METHODOLOGY

## 3.1 | Robust programming (RP) based on HRPP-I

Most parameters in the design of SC network problems face high levels of uncertainty in real situations because they are dynamic problems due to the unstable nature of the parameter values in long periods (Baghizadeh et al., 2021). Under such conditions, the final solution must be robust because it investigates the capacity specification decisions and allocation of position which do not change easily in the long run Accordingly, a new hybrid robust possibilistic programming (HRPP) approach is implemented in the present study to investigate the uncertain parameters in the proposed agriculture SC problem. RP and fuzzy programming (FP) approaches will be briefly introduced in the following.

Fuzzy mathematical programming (FMP) is used to manage two types of uncertainty including the inherent uncertainty of data and flexibility in the objective function and the elastic uncertainty of the constraints. In the first category, the uncertain coefficients in the objective function and related constraints are generally managed based on the available quantitative inputs and the qualitative knowledge of the decision makers. The second category, which is flexible, is about the decision-making process under the flexible value related to the function performance and constraint elasticity. Possibilistic chance-constrained programming (PCCP), one of the known methods of fuzzy programming, is used to deal with the potential data, such as the constraints that include the potential data on the left/right side (RHS) (Mousazadeh, et al., 2018a). The given method provides the minimum level of confidence ($\Psi$) for DM to meet possible constraints. Decision makers (DM) can determine the minimum level of confidence ($\Psi$) as the secure margin for the level of satisfaction of any possible chance constraint. According to the inherent uncertainty of the parameters in the SC, dealing with them is of great importance in this study. Demand for manufactured products frequently change and consequently, uncertain. This uncertainty poses many challenges for modeling and finding desirable solutions. To address and manage this, the model presented in this paper considers the solar panel budget, drip irrigation system budget and greenhouses production efficiency by using uncertainty in the constraints. Moreover, energy consumption and water consumption are uncertain in objective functions. In this problem, a variable that follows a trapezoidal probability distribution is used to model the uncertainty parameters, which are defined by four prominent points in Figure 2.

Possibilistic programming models with stochastic constraints can deal well with uncertain parameters. This model is not sensitive to the deviation of the objective function (OF) value from its expected value. Uneven and uncertain parametric values can cause many risks to DM in several real situations. Due to the mentioned problem of the proposed model, a hybrid robust possibilistic programming (HRPP-I) approach is implemented to combine the advantage of

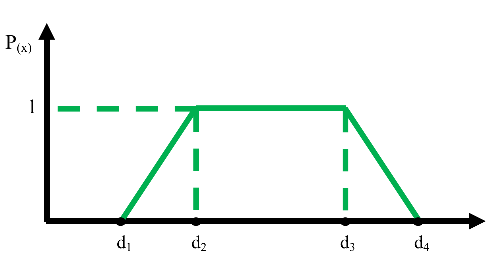


FIGURE 2 The trapezoidal possibility distribution of fuzzy parameter

both RP and FP approaches. This method is introduced by (Mousazadeh et al., 2018b) for the first time. the HRPP-I model can be expressed as follows:

$$\begin{aligned}
&Z^* = \min E[P] + \gamma(P_{\max} - P_{\min}) + \delta_1\left[\frac{(\varphi - \Upsilon)B_1 + (1-\varphi)B_2}{1-\Upsilon} - B_1\right].\,Y\\
&\quad + \delta_2\left[d_4 - \frac{(\sigma - \Upsilon)d_3 + (1-\sigma)d_4}{1-\Upsilon}\right]\\
&\text{s.t:}\\
&M \le \left[\frac{(\varphi - \Upsilon)B_1 + (1-\varphi)B_2}{1-\Upsilon}\right].\,Y\\
&M \ge \left[\frac{(\sigma - \Upsilon)d_3 + (1-\sigma)d_4}{1-\Upsilon}\right]\\
&A\cdot M = 0\\
&O\cdot Y \le 1\\
&M \le N.\,L\\
&G\cdot L \le 1\\
&Y, L \in \{0,1\}, M \ge 0, \varphi \ge 0.5, \sigma \le 1.
\end{aligned} \tag{47}$$

In the OF, the task of the first term (expected value of *z*) is to increase the expected performance of OF. The second term controls the optimality robustness of the final solution by reducing the difference between the upper and lower limits of OF. Here, $P_{\min}$ and $P_{\max}$ can be expressed as follows:

$$\begin{aligned} Z_{\max} &= Q_4\cdot Y,\\ Z_{\min} &= Q_1\cdot Y. \end{aligned} \tag{48}$$

In addition, the final two terms of possibilistic robustness control the final solution by minimizing the deviation of RHS from their best value (i.e. $B_1$ and $d_4$ where $\delta_1$ and $\delta_2$ are the unit penalty costs of these deviations). In addition, y is the weight of the significance of optimality robustness over the possibilistic robustness. Generally, the OF values can be evaluated using the interactive sensitivity analysis by making small changes in the confidence levels. The values that satisfy the DM preferences the most are selected as the final values. In addition, increasing the number of stochastic constraints helps to dramatically increase the number of tests required to determine the appropriate values of the confidence level. Therefore, based on Equation (50), constraints(10), (11), (31) and (32) will be converted as follow:

$$\sum_f SF_f \times dt_f \times CF \le \left[\frac{(\varphi - \Upsilon)CD_1 + (1-\varphi)CD_2}{1-\Upsilon}\right], \tag{49}$$

$$\sum_f SF_f \times PV_f \times PF \le \left[\frac{(\beta - \Upsilon)CP_1 + (1-\beta)CP_2}{1-\Upsilon}\right], \tag{50}$$

$$\sum_s QG_{sdt} + \sum QE_{sdt} \ge \left[\frac{(\sigma\text{-}\Upsilon)DF_{dt(3)} + (1\text{-}\sigma)DF_{dt(4)}}{1\text{-}\Upsilon}\right] \quad \forall\, t, d, \tag{51}$$

$$\sum_s QH_{sdt} + \sum_s QZ_{sdt} \ge \left[\frac{(\upsilon\text{-}\Upsilon)DN_{dt(3)} + (1\text{-}\upsilon)DN_{dt(4)}}{1\text{-}\Upsilon}\right] \quad \forall\, t, d. \tag{52}$$

The rest of constraints will not be changed. Deterministic modeling and robust modeling are implemented and defined in this section. The uncertain model is also described.

## 3.2 | Solution method

The multiobjective optimization model (discussed in Section 3) can be transformed into a single-objective mathematical model by employing the so-called ε-constraint method. Usually, it would take an extremely long time to try to solve the resultant single-objective model, even for medium-sized problems, by utilizing conventional solution methods. Using the LR method, this model may be solved within a certain period of time.

### 3.2.1 | Epsilon constraint method

The model proposed in the present paper is a MINLP model, which prioritizes profit, water waste and consumption, energy consumption, and, finally, waiting time. The ε-constraint method is among the prevailing techniques with a successful background to solve MOPs, introduced by (Haimes, 1973).

$$\mathrm{Min}_{\chi \in r}[P(r) = (P_1(r), P_2(r), \ldots P_k(r))]. \tag{53}$$

Here, OFs are prioritized such that the most significant one is taken as the main OF, and the others are added to the original model as constraints. DMs can indeed evaluate the effect of other functions on the problem by giving priority to profit functions as the main function. It starts to work by predefining a virtual grid in the objective space as well as by solving various single-objective optimization problems constrained to each grid cell. Hence, when the grid is sufficiently fine, all Pareto-optimal (PO) solutions can be reached so that maximally a single PO solution is contained in each cell (Mavrotas, 2009). The aim is to conquer the complexity of solving a multiobjective model by maximizing or minimizing a single objective at a time and expressing others as inequality constraints. Now, let us assume a MOP with K objective functions as Equation (53):

$$\mathrm{Min}\ \ P_k(r) \tag{54}$$

S.t:

$$P_i(r) \le \varepsilon_i \quad \forall i \in \{1, 2, \ldots, k\}, \tag{55}$$

where $x$ is decision variables vector, $P_{(r)}$ is notation for objective functions vector and $r$ is space of feasible solutions. Based on epsilon constraint method, the MO problem in Equation (53) will be converted to single objective problem as Equation (54) and Equation (55); where Equation (54) is primary objective function:

$$\mathrm{Min}[-Z_1(x)] \tag{56}$$

s.t

$$Z_2 \leq \varepsilon_2, \tag{57}$$

$$Z_3 \leq \varepsilon_3, \tag{58}$$

$$Z_4 \leq \varepsilon_4. \tag{59}$$

Therefore, the presented multiobjective model will be changed with the profit objective function as the primary one, as Equations (56)–(59):

### 3.2.2 | LR

A large-scale MINLP model was introduced in the preceding section, capable of being solved using commercial software such as GAMS. An increased solution problem size would lead to a sharp increase in problem dimensions. Thus, solving large polynomial problems by utilizing conventional techniques is impossible, and more optimal and efficient methods have been proposed instead (Fisher, 2004). Hence, the integrated optimization model has been solved in this paper using the LR method. It is among the most suitable techniques to solve SC problems, which have been shown to be efficient and robust. It can yield lower and upper bounds for the optimal OF value, contributing to the enhanced quality of their solution method as well as to determining the distance between the possible solutions and the optimal solution (Fahimnia et al., 2017).

The LR method used in this paper is composed of three major steps. The first step involves obtaining a lower bound for the optimal solution. The second step involves obtaining an upper bound for the optimal solution. Finally, the third step involves updating lower/upper bound values if the ones obtained in the last two steps are not sufficiently close. This procedure continues until lower/upper bound values reach a certain threshold.

*Determination of the lower bound*

To determine the lower bound, certain constraints were relaxed to promote the problem solution, although the solution cannot be sought (Fisher, 2004). Here, the problem-solving procedure was facilitated by relaxing the constraints (14) and (15).

Upon the relaxations performed, these two constraints will be eliminated from constraint equations and the first objective function will be as below:

$$\begin{aligned} Min\,\mathrm{W}(\mathrm{U}^2_{ft}, \mathrm{U}^1_{ft}) = Min\,(-Z^*) + \textstyle\sum_t \sum_f \mathrm{U}^1_{ft}[QP_{ft} - Mins \times dt_f \times SF_f \times RF_f] \\ + \textstyle\sum_t \sum_f \mathrm{U}^2_{ft}[QS_{ft} - Mins \times dt_f \times SF_f \times NF_f]. \end{aligned} \tag{60}$$

In the OF above, $U^2_{lmn}$ and $U^1_{ijn}$ values are non-negative-valued Lagrangian coefficients. The relation above was minimized using fixed-valued Lagrangian coefficients. The optimal value of the Lagrangian duality model is, therefore, the lower bound.

*Determination of the upper bound*

As per the relaxation of constraints (14) and (15), in most cases, the solution to the Lagrangian dual problem is unfeasible. The feasible solution can thus be obtained by solving the model based on Equation (63) and constraints. This is the upper bound of the problem.

*Updating lower/upper bounds*
Lagrangian coefficients are updated to the new values at each repetition of Lagrange's method, which is iteratively generated for lower/upper bounds. At each repetition of the problem, Lagrangian coefficients are calculated as follows, as introduced by Fisher (2004):

$$U_{ft}^{1,x+1} = \max\left\{0, U_{ft}^{1,x} - stp_{1,x} \times \left(\sum_t \sum_f [QP_{ft} - Mins \times dt_f \times SF_f \times RF_f]\right)\right\}, \tag{61}$$

$$U_{ft}^{2,x+1} = \max\left\{0, U_{ft}^{2,x} - stp_{2,x} \times \left(\sum_t \sum_f [QS_{ft} - Mins \times dt_f \times SF_f \times NF_f]\right)\right\}. \tag{62}$$

In Equations (61) and (62), $x$ is the number of repetitions; $stp_{1,x}$ and $stp_{2,x}$ are calculated as follows:

$$stp_{1,x} = \frac{\nu_x \times (UP - LB_x)}{\sum_t \sum_f [QP_{ft} - Mins \times dt_f]^2}, \tag{63}$$

$$stp_{2,x} = \frac{\nu_x \times (UP - LB_x)}{\sum_t \sum_f [QP_{ft} - Mins \times dt_f]^2}. \tag{64}$$

In Equations (63) and (64), $UP$ and $LB_x$ are the best upper/lower bounds found in the $Stp$ repetition, respectively. The $\nu$ value was assumed to be 2 at the onset of the solution method. If $LB$ does not improve after five repetitions, the new $\nu$ will be half of the previous $\nu$. The problem-solving process comes to an end, based on two conditions:

- Obtaining a feasible solution with an acceptable tolerance.
- *Stp* has reached its minimum possible value.

## 3.3 | Computational results

In this section, 15 numerical examples with different sizes are presented to validate the model and its solution approach that is presented in the previous section. Therefore Table 1 is presented to provide some of input parameters.

It should be noted that all the numerical examples are conducted using GAMS windows application on a laptop with Windows 10, Intel Core i7 CPU and 8GB of RAM. As mentioned in the previous section, the approach to converting a multiobjective model to a single-objective model is the Epsilon constraint that illustrates the Pareto front. Figures 3 and 4 present the Pareto-Front for the main objective function (profit maximization) and the other objective functions individually.

In the next step, 15 numerical examples are solved through the software solver of GAMS without using the LR method. Then, the model is solved using the LR method, and its results, including "objective function," "solution time," and "difference between objective functions," are presented in the form of Table 2, Figures 3 and 4.

As provided in Table 2, by increasing the size of the problem and the complexity of numerical computations, a significant difference is created in the solving time of the model with

TABLE 1 Values of input parameters

| Parameter | Value | Unit |
|---|---|---|
| $SF_f$ | 490, 693, 376, 550, 750, 582, 747 | Square meters ($m^2$) |
| *CF* | 22,000 | Toman |
| *PF* | 59,000 | Toman |
| *VF* | 23,500 | Toman |
| *Vb* | 23,500 | Toman |
| *Vd* | 29,000 | Toman |
| *Vs* | 24,000 | Toman |
| *FR* | Uniform (0.2, .03) | Liter |
| FC | 750 | Toman |
| *WC* | Uniform (220, 240) | Liter |
| *WT* | Uniform (340, .390) | Liter |
| *HC* | 190 | Toman |
| *CN* | 440 | Toman |
| *CRW* | Uniform (50, .60) | Liter |
| *CNW* | Uniform (65, 80) | Liter |
| $NV_{Fw}$ | 11 | |
| $NV_{FS}$ | 6 | |
| *CV* | 75 | kg |
| *TX* | (170, 195) | Toman |
| $K_{FS}$ | 6 | |
| *PC* | 400 | Toman |
| *CN* | 300 | Toman |

and without LR, which shows how much faster the problem is solved through LR, and also indicates the effectiveness of this method. However, GAMS solver was not able to solve problems numbers 12–15. Figure 5 indicates the run time obtained from solving methods with and without LR. As the dimensions of the problem increase, the objective function significantly increases in the successive repetitions. Figure 5 shows the solving time of the model with and without LR algorithm. Clearly, there is no significant difference between the solving times of these two methods when the size of the problem is small. However, in the medium and large dimensions, the LR method requires much less time for solving the problem as the solving time of the method without LR is significantly increased. Therefore, it can be concluded that, this solution method is more efficient and cost effective than epsilon constraint method.

Figure 6 also shows the difference in percentage of the objective function values when solving the problem with and without LR. As you can see, in the smaller dimensions, this value is small and insignificant, and in the larger dimensions the difference is acceptable.

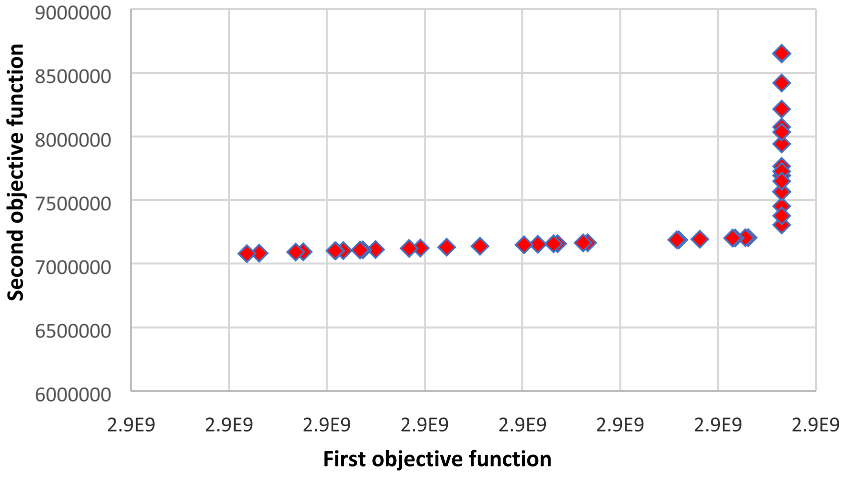


FIGURE 3 First objective function and second objective function Pareto front

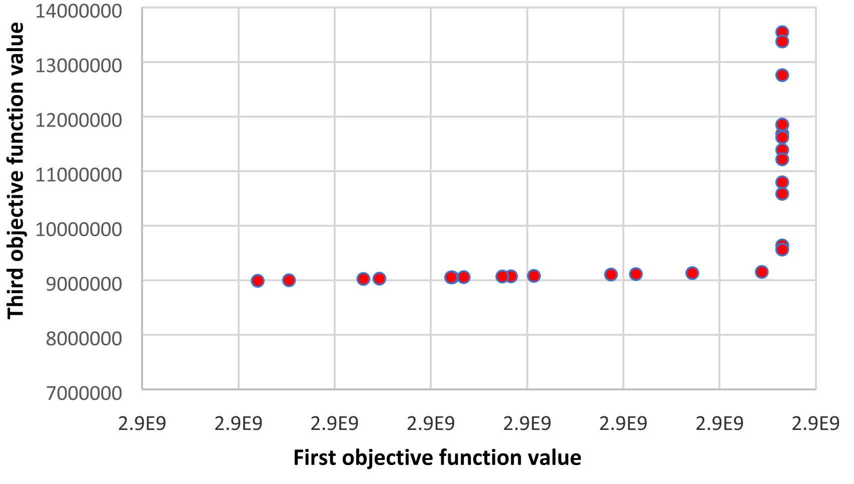


FIGURE 4 First objective function and third objective function Pareto front

## 4 | CASE STUDY

According to the implementation of the LR algorithm and the proof of its effectiveness and efficiency in large-scale problems, the model can be verified on a real problem. Therefore, in this section, the MINLP multiperiod and multiobjective mathematical model that is proposed for greenhouse productions is implemented for a fruit production company in Iran. In fact, the main purpose of this implementation is to evaluate and observe the capabilities of the proposed model in the related industry.

Since factors such as water consumption, energy consumption, production volume, pollution, costs, decay, and disposal of agricultural products are of great importance in the agricultural industry, this study has tried to cover all of these issues. The main purpose of designing this SC, which has a water-energy-food approach, is to maximize profit. The other objectives are reducing water and energy consumption along with decreasing waiting time based on

**TABLE 2** The results of the developed epsilon-constraint method and Lagrangian relaxation

| Problem number | Problem size | Indices | | | | | | GAMS | | LR | | Optimality gap |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *f* | *w* | *s* | *d* | *j* | *t* | Run time | Obj value | Run time | Obj value | |
| 1 | Small | 1 | 1 | 1 | 1 | 1 | 2 | 0/15 | 4,210,931/56 | 0/22 | 4,210,931/56 | 0/000000% |
| 2 | | 2 | 1 | 2 | 1 | 1 | 2 | 0/167 | 3,929,112/805 | 0/29 | 3,929,112/805 | 0/000000% |
| 3 | | 2 | 2 | 2 | 2 | 1 | 2 | 0/291 | 6,134,010/11 | 0/394 | 6,134,010/11 | 0/000000% |
| 4 | | 3 | 3 | 3 | 2 | 1 | 2 | 2/77 | 13,466,044/83 | 0/79 | 13,466,044/83 | 0/000000% |
| 5 | | 3 | 3 | 4 | 2 | 2 | 3 | 4/53 | 24,962,610/07 | 1/96 | 24,962,610/07 | 0/000000% |
| 6 | Medium | 3 | 3 | 4 | 4 | 2 | 3 | 7/46 | 30,621,830/06 | 2/25 | 30,621,830/06 | 0/000000% |
| 7 | | 3 | 3 | 4 | 5 | 2 | 3 | 25/39 | 51,278,151/06 | 4/9 | 51,278,199/06 | 0/000094% |
| 8 | | 3 | 4 | 4 | 6 | 3 | 3 | 59/42 | 62,194,190/06 | 9/23 | 62,194,307/06 | 0/000188% |
| 9 | | 4 | 4 | 5 | 7 | 3 | 4 | 84/76 | 83,153,044/46 | 14/41 | 83,153,410/46 | 0/000440% |
| 10 | | 5 | 5 | 6 | 7 | 3 | 4 | 149/61 | 109,517,028/1 | 21/91 | 109,517,408/1 | 0/000347% |
| 11 | Large | 6 | 6 | 6 | 9 | 4 | 4 | 201/409 | 260,344,221/5 | 34/91 | 260,345,691/5 | 0/000565% |
| 12 | | 6 | 7 | 6 | 10 | 4 | 5 | - | - | 47/92 | 472,481,892 | |
| 13 | | 7 | 8 | 7 | 10 | 5 | 6 | - | - | 99/24 | 785,020,819/6 | |
| 14 | | 8 | 8 | 7 | 11 | 5 | 7 | - | - | 142/09 | 1,059,615,355 | |
| 15 | | 9 | 9 | 8 | 12 | 6 | 7 | - | - | 207/11 | 1,521,308,342 | |

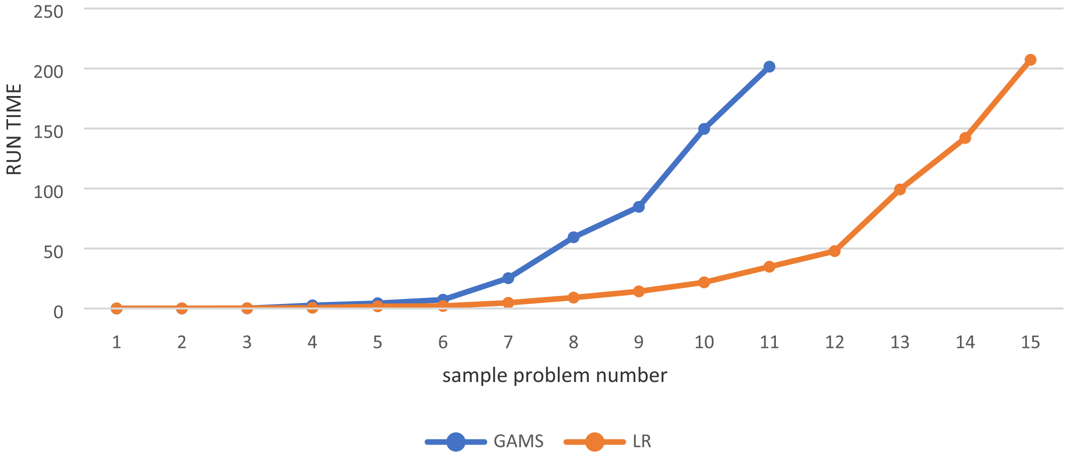


**FIGURE 5** Run time obtained from solving methods with and without LR

G/M/S//M, which have not yet been studied separately. As an experimental study, the strawberry production SC is responsible for locating warehouses, determining the capacity of the distribution centers, determining the amount of production, applying drip irrigation system, solar panels for greenhouses, and transportations.

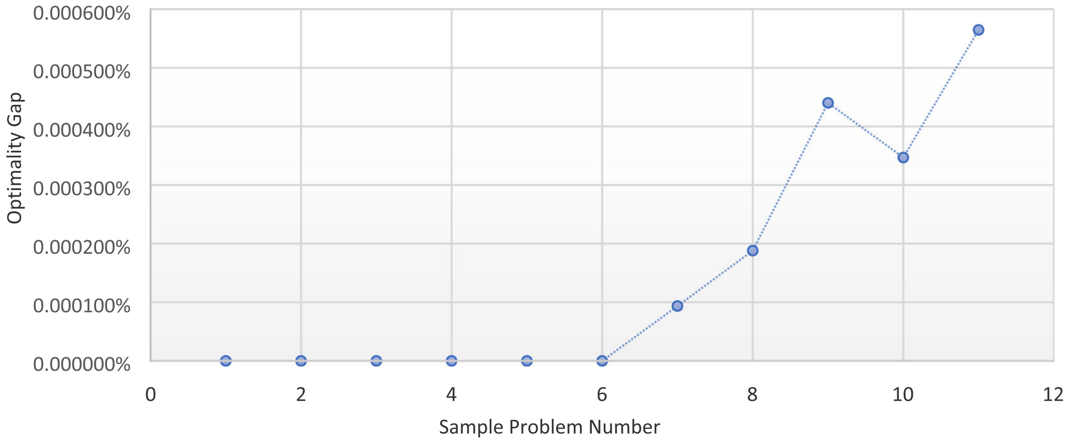


**FIGURE 6** Difference percentage of the objective function values with and without LR method

The case study of the present investigation is performed on a fruit production company branded as "Haft Mive" that is currently active in Tehran. This company owns several greenhouses producing off-season products. To date, all of the greenhouses have been equipped with traditional irrigation systems and fossil fuel-based energy generation systems. The company is planning to upgrade the greenhouses and equip them with drip irrigation systems and solar panels, based on financial aids by the government. In addition, the company is arranging to produce organic products at a higher price compared to the inorganic products in their new working season. Moreover, due to the lack of warehouse capacity, some of the products are always discarded. Out of the eight potential warehouses, with specified capacities, the company aims to use five to store the strawberry products of seven owned greenhouses. The products sent to the well-equipped warehouses are packaged to prevent their decay in each cycle. According to the proposed model, the productions in excess of the warehouse capacity are shipped directly to the distribution centers to be distributed without packaging. This avoids the disposal of these products as in the past. The products that are in excess of the capacity of distribution centers are discarded. The strawberries that are decayed in the SC are sent to jam production factories. The suggested model for this company consists of technical and tactical decisions. Selecting the best warehouses, specifying the quantity of production, applying drip irrigation systems, greenhouse solar panels, and the quantity of organic and inorganic strawberry production are among these decisions. The mentioned decisions are made in accordance with the objectives such as increasing profits, decreasing water and energy consumption, transportation and waiting time, and environmental impacts.

Figure 7 shows the map of Tehran in which the existing greenhouses, potential warehouses, distribution centers of "Haft Mive" company, customer zones, and the jam production factories are identified. It should be noted that the transportation expenses and the decay rate are determined in accordance with their distance due to the differences in distances between the facilities. The proposed model is implemented for six time periods, which indicates 6 months of greenhouse strawberry production.

The optimal net profit from the company's productions is estimated to be 472,479,591.966,827 Tomans (local currency). The optimal solution to the problem based on the second objective function indicated that optimal water consumption is 374,924.07 L. In addition, energy consumption has reached 1,720,321.94 J. For the final objective function, waiting time and transportation time in two

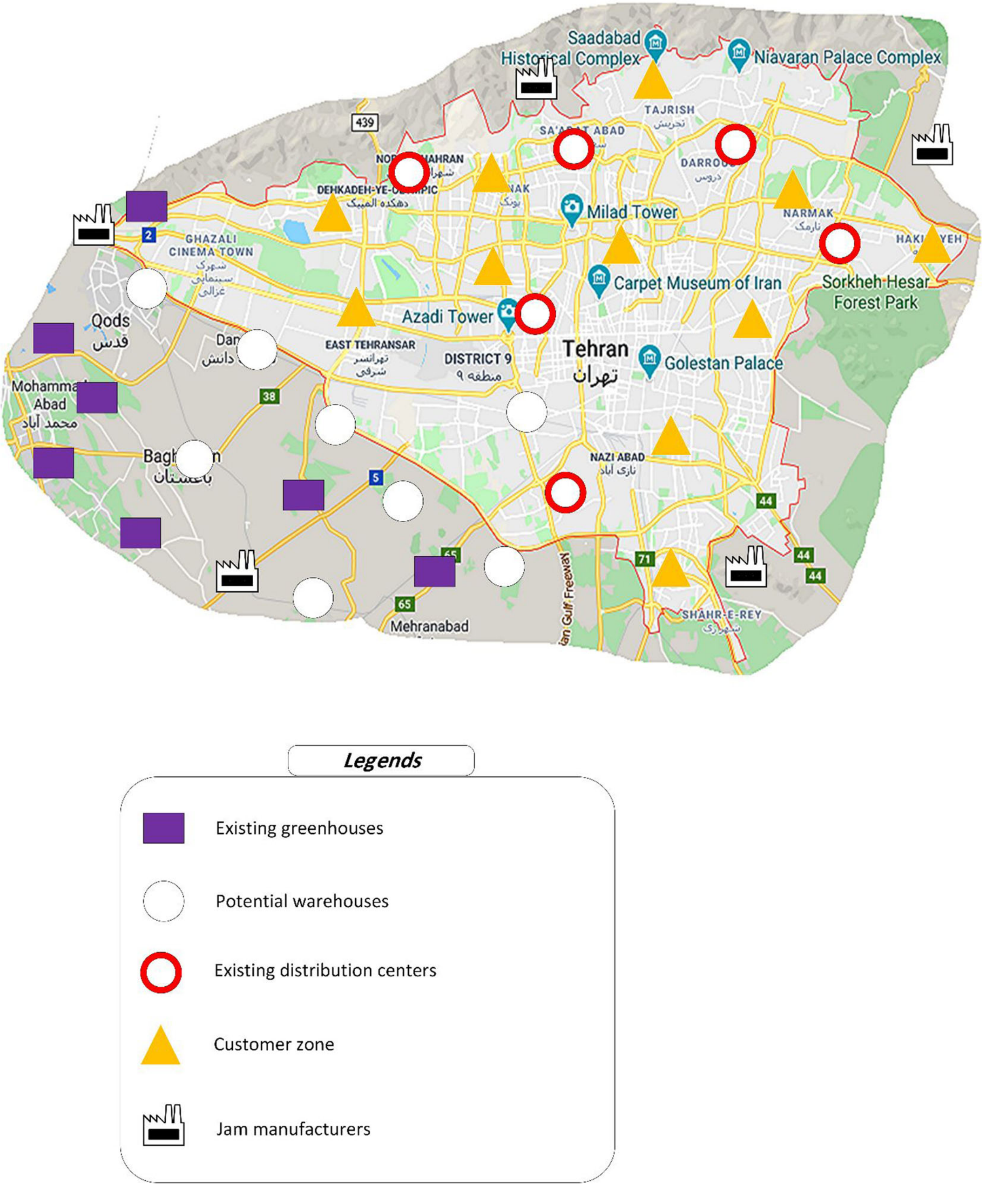


**FIGURE 7** Geographical location of candidate and exist facilities

directions, greenhouses to warehouses and greenhouses to distribution centers is equal to 7892.362 min. A number of optimal variables value are presented in Tables 3–7.

Table 7 demonstrates the optimal conditions for binary variables in terms of production and equipment based on the optimal solution.

Some of queuing system results of solving the case study with LR method are indicated in Figure 8. As can see, Figure 8 shows total waiting time for loading and total length of queue for loading in each period.

# 5 | MODEL ANALYSIS

## 5.1 | Sensitivity analysis

A sensitivity analysis is performed to study different aspects of the problem, and realize which of the major parameters are the most influential in the proposed model. This analysis is carried out on a set of variations in important parameters of the problem to clarify the way the variations in each parameter affect the final solution of the problem. In this article, the sensitivity analysis is performed on four major parameters, including the amount of allocated budget for implementing the drip irrigation system, the capacity of the warehouses, the total demands, and the allocated budget for equipping the greenhouses with solar panels. For the last objective function, sensitive analysis will be performed on different major parameters. Eventually, their effect is identified on each of the objective functions. After performing the sensitivity analysis, the effectiveness of each parameter is reported to improve each objective function assisting the experts and administrators with making the best decisions.

### 5.1.1 | Sensitivity analysis of profit objective function

As stated previously, the first objective function of the problem is dedicated to network profitability. The profit objective function generally consists of the difference between the income from the sale of strawberries and total costs of the network. Figure 9 shows the effects of the four previously mentioned parameters on maximizing SC profits. As can be seen, the profitability of the SC increased with an increase in warehouse capacity. More specifically, profitability increased by 7% with only a 5% increase in warehouse capacity, while there is an 8%

**TABLE 3** Optimal value of QA

| Indices | | *T* (period time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** |
| 2 | 1 | | 5132/195 | 1394/282 | 4513/024 | 5132/195 | |
| 2 | 4 | | | | | | 5132/195 |
| 2 | 5 | | | 0/18,595 | | | |
| 2 | 6 | 3055/544 | | | 619/1711 | | |
| 5 | 1 | | 4108/752 | | 3739/159 | 4886/378 | |
| 5 | 2 | | | | | 83/91,655 | 491/6175 |
| 5 | 4 | | | 531/537 | | | |
| 5 | 5 | | | | 1707/862 | | 1445/104 |
| 5 | 6 | 6267/341 | 443/8202 | 5735/804 | | | |
| 6 | 1 | | | | 2034/138 | | 5426/318 |
| 6 | 4 | | 3093/597 | | | | |
| 6 | 5 | 2711/624 | 322/5379 | | | | |
| 6 | 6 | | | 5008/596 | | 2581/893 | |

**TABLE 4** Optimal value of QE

| Indices | | *T* (period time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 2 | 629/9102 | | | | | |
| 1 | 4 | 1022/864 | | 755/19 | | | |
| 1 | 5 | 1013/724 | | 413/4214 | | | |
| 1 | 6 | 715/7624 | | 406/5926 | | | |
| 1 | 7 | 789/0619 | | 662/7747 | | | |
| 2 | 1 | 899/0042 | | | 45/40342 | | |
| 2 | 2 | | | 667/1849 | | | 351/5919 |
| 2 | 3 | | | 123/572 | | 539/482 | 210/7428 |
| 2 | 4 | | | | 636/25 | | 497/6038 |
| 2 | 5 | | | | | | 392/3477 |
| 2 | 6 | | 511/0801 | | | 633/0232 | 494/7968 |
| 2 | 7 | | 306/794 | | 797/9621 | 564/8878 | |
| 2 | 8 | | 413/0389 | | 954/0719 | 432/7694 | |
| 2 | 9 | | 352/5698 | | 521/9633 | 471/2147 | |
| 2 | 10 | | 539/7539 | | 574/4318 | 535/5258 | |
| 2 | 11 | | | | | 556/6512 | |
| 3 | 1 | 188/9246 | | | | | 600/0047 |
| 3 | 2 | | | | | 1014/124 | 290/1535 |
| 3 | 3 | 265/232 | | | | 329/7931 | 290/1535 |
| 3 | 4 | | | | | | 290/1535 |
| 3 | 5 | | | | | | 290/1535 |
| 3 | 6 | | | | | 329/7931 | 290/1535 |
| 3 | 7 | | | | | 329/7931 | 445/2386 |
| 3 | 8 | | | | | 329/7931 | 3/151,301 |
| 3 | 9 | 310/311 | | | | 329/7931 | 702/5329 |
| 3 | 10 | 329/7931 | | | | 329/7931 | 858/453 |
| 3 | 11 | 107/6639 | | | | 329/7931 | 3/151,301 |
| 4 | 10 | | | 445/8498 | | | |
| 5 | 1 | | | 379/3815 | | | |
| 5 | 2 | | | 329/7931 | | | |
| 5 | 3 | | | 329/7931 | | | |
| 5 | 4 | | | 329/7909 | | | |
| 5 | 5 | | 841/9321 | 329/7909 | | | |

(Continues)

**TABLE 4** (Continued)

| Indices | | T (period time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 5 | 6 | | 205/0859 | 329/7909 | | | |
| 5 | 7 | | 205/0859 | 329/7909 | | | |
| 5 | 8 | | 205/0859 | 765/2514 | | | |
| 5 | 9 | | 205/0859 | 46/08615 | | | |
| 5 | 10 | | 205/0859 | 329/7931 | | | |
| 5 | 11 | | | 46/08615 | | | |
| 6 | 1 | | 851/8292 | | 905/789 | | 160/3618 |
| 6 | 2 | | | | 1061/36 | | 290/1535 |
| 6 | 3 | | | | 188/6436 | | 290/1535 |
| 6 | 4 | | 980/3728 | | 212/6529 | | 290/1535 |
| 6 | 5 | | | | | | 290/1535 |
| 6 | 6 | | 205/0859 | | | | 290/1535 |
| 6 | 7 | | 205/1906 | | 212/6529 | | 16/39582 |
| 6 | 8 | | 205/0859 | | 212/6529 | | 3/151,301 |
| 6 | 9 | | 205/0859 | | 212/6529 | | |
| 6 | 10 | 505/0134 | 205/0859 | | 212/6529 | | |
| 6 | 11 | | | | | | 3/151,301 |

drop in profitability with a 5% decrease in warehouse capacity. However, an increase of about 33% can be observed in the profit objective function with a 25% increase in the warehouse capacity, which is a considerable value regarding the low costs of capacity increase. The reason for this is a reduction in decay due to decreased transportation between greenhouses and distribution centers. Generally, the amount of profitability increases with an increase in uncertain demands. Correspondingly, the profit increased by 37.7% with a 25% increase in this parameter. Two other parameters of major importance, which appear to be more environmentally friendly and economical, are also investigated to determine their effects on the profitability.

In general, the profit increased by increasing the allocated budgets for equipping greenhouses with drip irrigation systems. A 12.6% profit is observed by only a 10% increase in this budget. However, a distinctive profit of 24.2% is observed by increasing this budget to 25%. In fact, the use of the drip irrigation system not only reduces the water consumption but also the energy costs for water transfer. In addition, increasing budgets related to equipping greenhouses with solar panels also exhibited similar performance. With only a 5% increase in this budget, the profitability increased by 4%. In addition, a 21.5% profit increase is observed by a 25% increase in the budget. The reason behind this is the reduction of dependence and energy consumption for heating and other equipment.

TABLE 5 Optimal value of QH

| Indices | | T (period time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 3 | | 423/8452 | | | | |
| 1 | 4 | | | 1080/544 | | | |
| 1 | 6 | 1033/711 | | | | | 1283/725 |
| 1 | 7 | 877/1848 | | | | | 1084/773 |
| 1 | 8 | 1047/776 | | | | | 522/9703 |
| 1 | 9 | | | 1279/596 | | | |
| 1 | 10 | | 1193/943 | | | | |
| 1 | 11 | | | 598/5312 | 572/4148 | 840/1618 | |
| 2 | 1 | | | | 1220/644 | 1016/626 | |
| 2 | 2 | | | | 691/586 | 379/0418 | |
| 2 | 3 | | 417/7227 | | | | |
| 2 | 7 | | | | | | 67/20319 |
| 2 | 10 | | | | | 50/26,448 | |
| 2 | 11 | | | | 474/0271 | 213/7143 | |
| 3 | 2 | | 427/0339 | | | | |
| 4 | 1 | | 31/82,964 | | | | |
| 5 | 1 | | 464/2971 | | | | |
| 5 | 8 | | | | | 458/8636 | |

According to the results, the most effective parameter in improving the profitability of the proposed SC is achieved by increasing the capacity of warehouses by 25%. Overall, the drip irrigation system and solar panels did not increase costs, displayed a decent performance and increased the profit. With a similar amount of budget increase, however, drip irrigation has a greater influence on profit growth than the solar panel.

### 5.1.2 | Sensitivity analysis of water consumption minimization objective function

Large amounts of water consumption and waste are some of the most important concerns in the agricultural industry. A very large percentage of the water consumed by each community is related to its agricultural industry; therefore, its management and analysis appear to be vital. Hence, this section investigates the impacts of important parameters of the problem on this challenging issue.

The effects of four important parameters of the problem are shown in Figure 10. As can be observed, increasing the warehouse capacity leads to decreases in water waste and consumption. Since the products in excess of the capacity are shipped to distribution

**TABLE 6** Optimal value of QZ

| Indices | | T (period time) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 1 | | 777/8021 | | | | |
| 1 | 3 | | 241/234 | 1045/712 | | | 1040/399 |
| 1 | 4 | | | | 1284/511 | 1056/682 | |
| 1 | 5 | | 1120/404 | | 1115/167 | 1097/228 | |
| 1 | 6 | | 1178/967 | | 1013/52 | 1234/931 | |
| 1 | 7 | | 1182/202 | | 1178/22 | 1203/956 | |
| 1 | 8 | | 1197/068 | | 1037/319 | 837/1526 | |
| 1 | 9 | | 1233/033 | | 1060/372 | 1089/141 | 690/4551 |
| 1 | 10 | | | | 1025/631 | 994/8398 | 1130/257 |
| 1 | 11 | | | | | | 1208/628 |
| 2 | 9 | | | | | | 368/7132 |
| 2 | 11 | | | | | 62/93741 | |
| 4 | 1 | | | | | | 1172/89 |
| 4 | 2 | | | 398/6528 | | | 1067/725 |
| 4 | 4 | | 1112/39 | | | | 1089/253 |
| 4 | 5 | | | | | | 519/2788 |
| 4 | 11 | | 1207/808 | | | | |
| 5 | 1 | 831/0218 | | | | | |
| 5 | 2 | | 241/9034 | | | | |
| 5 | 3 | | | | 1280/897 | | |
| 5 | 5 | | | | | | 538/3615 |
| 5 | 8 | | | | | | 545/4666 |
| 5 | 9 | 1202/696 | | 0/139463 | | | |
| 6 | 1 | 287/9835 | | 1035/873 | | | |
| 6 | 2 | 1015/422 | 332/8651 | 721/7155 | 464/3783 | 809/6213 | |
| 6 | 3 | 1118/836 | | | | 1126/798 | |
| 6 | 4 | 1115/817 | | | | | |
| 6 | 5 | 1022/366 | | 1030/507 | | | |
| 6 | 6 | | | 1153/435 | | | |
| 6 | 7 | 301/7539 | | 1108/753 | | | |
| 6 | 8 | | | 1157/164 | | | |
| 6 | 10 | 1073/904 | | 1220/492 | | | |
| 6 | 11 | 1056/081 | | 630/361 | | | |

**TABLE 7** Optimal condition of each greenhouse in case study

| Greenhouse | Solar panel | Drip irrigation system | Organic product |
|---|---|---|---|
| 1 | 1 | 0 | 1 |
| 2 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 |
| 4 | 1 | 1 | 0 |
| 5 | 1 | 1 | 0 |
| 6 | 1 | 0 | 1 |
| 7 | 1 | 1 | 0 |

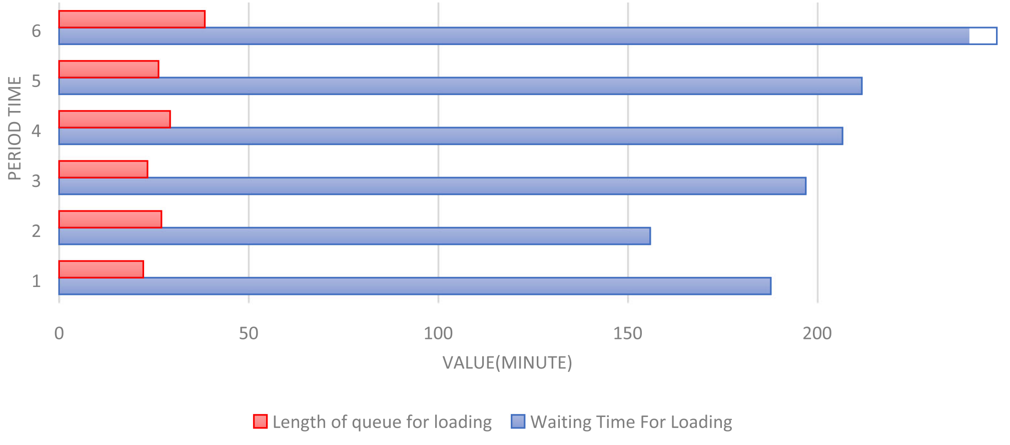


**FIGURE 8** waiting time and length of queue for loading

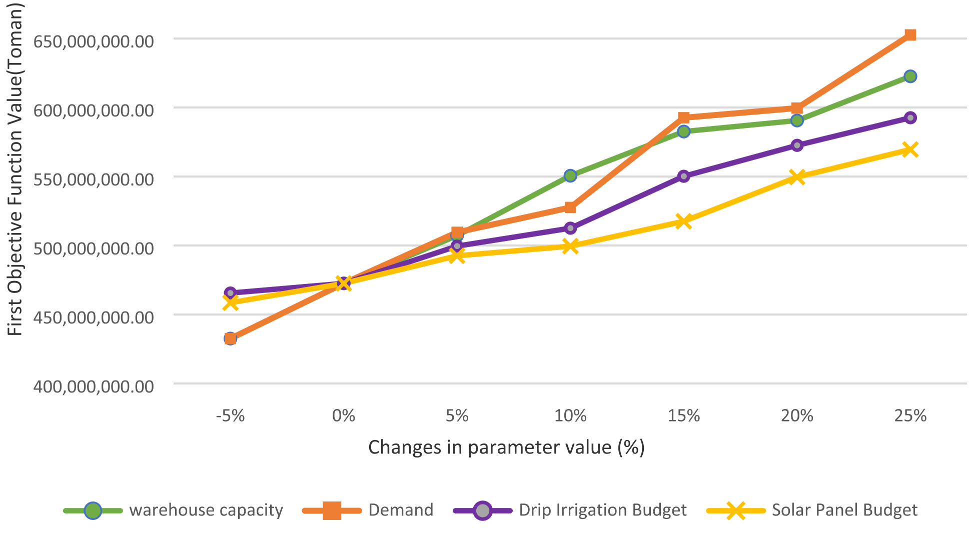


**FIGURE 9** Sensitivity analysis of the first objective function by changing the important parameters

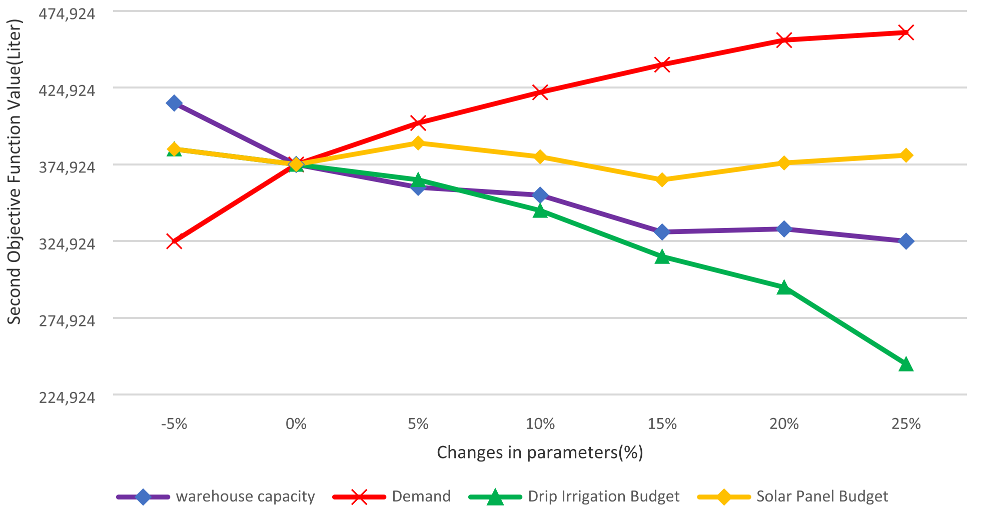


**FIGURE 10** Sensitivity analysis of the second objective function by changing the important parameters

centers, their decay rate increases intensely; therefore, it leads to an indirectly increase in water waste. The significance of this issue becomes very apparent when only a 5% decrease in warehouse capacity leads to an 11% increase in this objective function. In the best situation, on the other hand, a 15% increase in warehouse capacity results in a 12% reduction in water consumption and waste. The situation does not improve by increasing the capacity to 25%. Normally, more production is required to meet the increased demand. With a 25% increase in demand, water consumption increased up to 22.9%, indicating that more water waste management is required with increasing demand. Drip irrigation system is the most effective tool to reduce water consumption and waste. As shown in Figure 10, increasing the budget for drip irrigation equipment decreases the second objective function of the problem. Similarly, with only 5% and 25% increases in the budget of this equipment, a 4% decrease and a significant decrease of 34.7% are respectively reported in water consumption and waste.

According to Figure 10, it is clear that equipping greenhouses with solar panels did not help to reduce water consumption significantly. Therefore, it should be acknowledged that using drip irrigation systems in greenhouses is the best solution to the problem. Second, increasing warehouse capacity also leads to a relative improvement in water waste reduction.

### 5.1.3 | Sensitivity analysis of energy minimization objective function

Demand for agricultural and food products have increased significantly in recent years due to the population growth, leading to an increase in energy consumption. For this reason, it is important to study the parameters that affect energy consumption. Figure 11 shows the sensitivity analysis of the four parameters affecting the third objective function. As can be followed from the chart, energy consumption increases significantly by increasing demand. Furthermore, a 10% increase in uncertain demand leads to an 11.3%

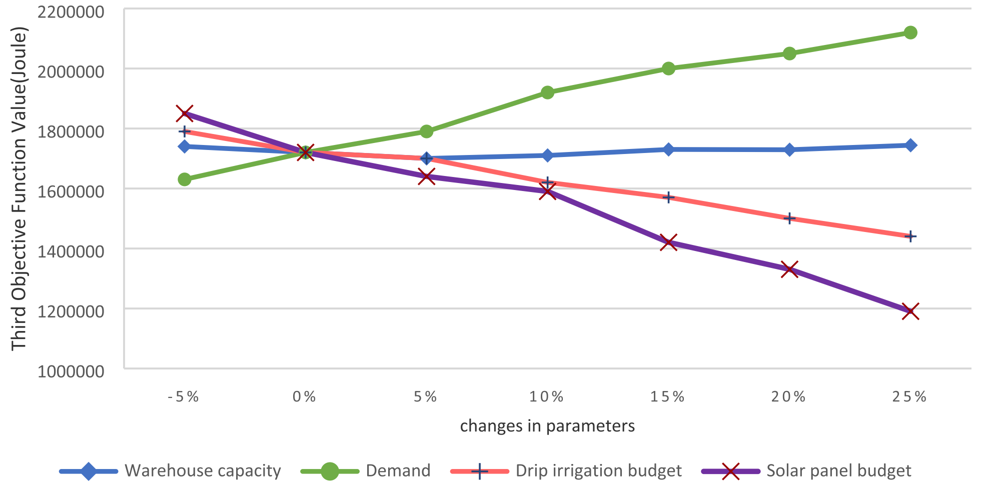


**FIGURE 11** Sensitivity analysis of the third objective function by changing the important parameters

increase in energy consumption while a 25% rise in demand raises energy consumption by 22.2%. This growth in energy is due to the consumption of more fossil fuels and solar energy to provide an appropriate temperature in addition to water transfer for irrigation. As shown in Figure 11, energy consumption decreases by using a drip irrigation system, as it requires less energy for an efficient water transfer.

As can be seen, a significant reduction is observed in energy consumption with the budget increase for equipping greenhouses using drip irrigation systems. Correspondingly, a 15% increase in this budget decreased energy consumption to 8.7%. If this budget increases to 25%, it can decrease energy consumption to 16.2%. One of the most important cases of energy consumption in greenhouses is to provide an appropriate temperature to grow agricultural products. Solar panels are among the best equipment for decreasing energy consumption to achieve this goal. As shown in Figure 11, increasing the budget of solar panels effectively reduces energy consumption, where the energy consumption drops to 17.4% with only a 15% increase in this budget. If this budget can be increased up to 25%, it will save 30.8% of energy, which will be a significant amount.

According to Figure 11, solar panels and the drip irrigation system make a significant contribution to reducing energy consumption. Hence, the first priority should be to equip greenhouses with solar panels to control energy consumption, leading to maximum energy savings. Equipping greenhouses with drip irrigation systems comes second in terms of decreasing energy consumption.

### 5.1.4 | Sensitivity analysis of G/M/S//M queue theory and waiting time objective function

The behavior of the G/M/S//M queue method and last objective function can be better understood by analyzing its sensitivity to changes in relative parameters. Accordingly, a sensitivity analysis is performed on the number of transport fleets. As shown in Figure 12, the objective

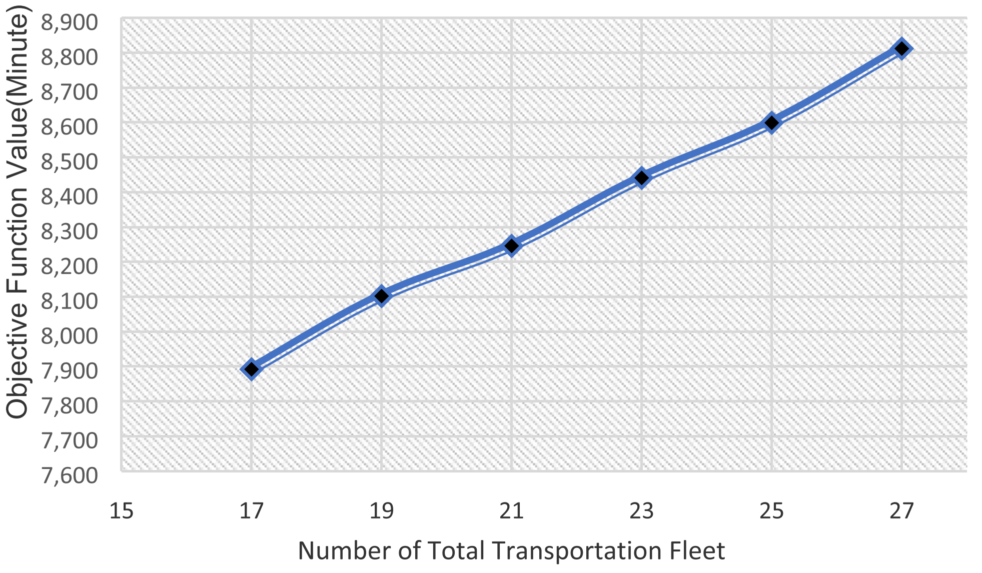


**FIGURE 12** Sensitivity analysis of the last objective function by changing the number of transportation fleet

function will experience an upward trend by an increased number of transport fleets, which in turn leads to increased queue length at loading centers and consequently increased environmental impact by network vehicles. Thus, the objective function increases with an increase in waiting time.

As it is shown in Figure 13, the increased number of transport fleets also increases the amount of unloading at loading centers. Since no queue is formed at unloading centers, this chart does not have a sharp upward slope; therefore, there will be no considerable increase in the amount of unloading.

A sensitivity analysis is then applied to transport fleet capacity. Figures 14–16 show the association between transport fleet capacity and last objective function/queue length/waiting time. The time required to load each transport fleet increases as a result of increased transport fleet capacity. Hence, as service time increases for each of the customers, waiting time and queue length increase as well. The objective function is comprised of two major parts: waiting time and transport. The first part decreases as a result of increasing the waiting time and queue length. The model seeks to minimize the objective function, so there is an optimal solution, which reduces the sum of transport and waiting times. Optimality, as well as increased capacity, can be achieved by increasing queue length until minimization of the sum and amount of demand is ensured. A larger number of products can be transported by increasing fleet capacity, which in turn reduces the number of shipments and, as a consequence, the queue length after a certain point. Hence, increased capacity can cause an increase in queue length. Following the transfer of a greater number of products, the number of shipments decreases to meet demand, leading to a drop in the waiting time and queue length (Figures 14 and 15).

Figure 16 shows the link between the objective function and the transport fleet capacity. The first part of the objective function decreases initially due to increased vehicle capacity,

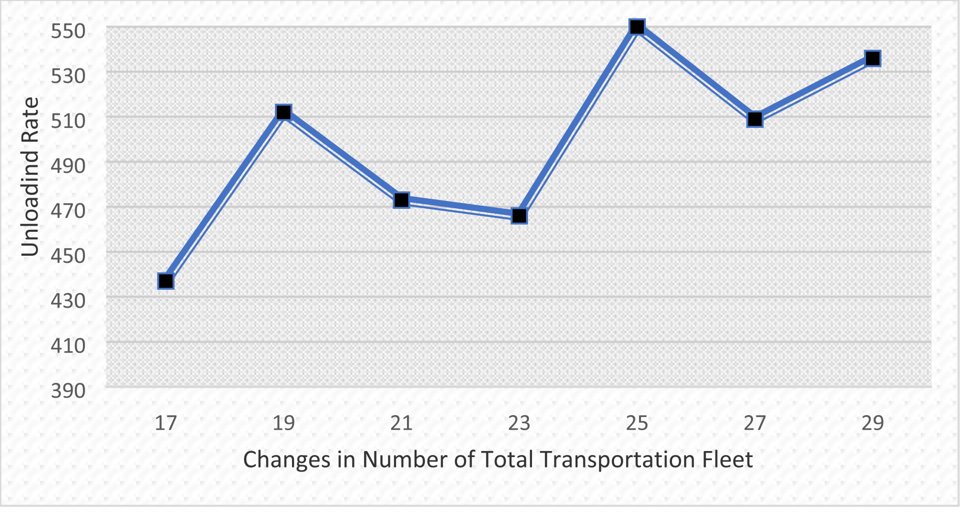


FIGURE 13 Unloading rate versus number of transportation fleet

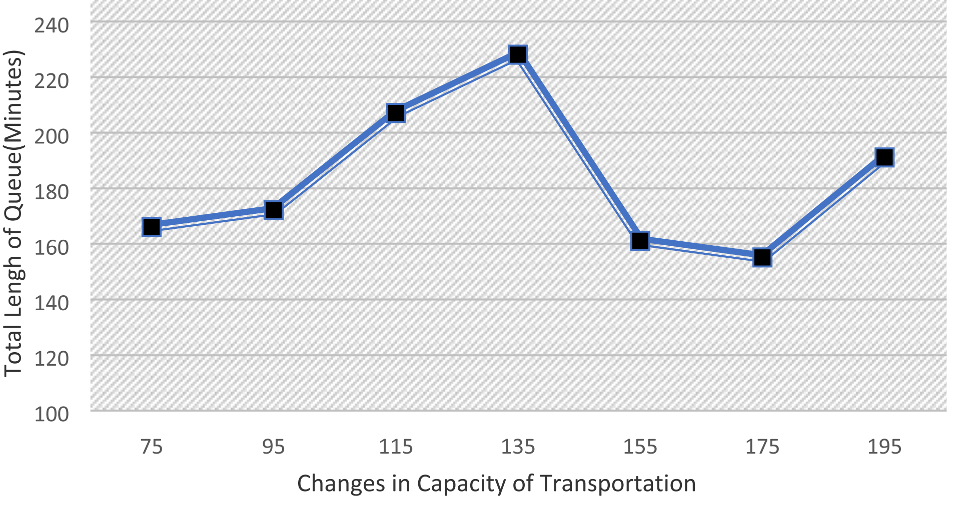


FIGURE 14 Total length of queue versus capacity of transportation

indicating reduced transport time between centers. The objective function depends on transportation cost per unit of distance, so when the latter increased, the former is reduced. In addition, a large number of vehicles can be accessed at loading centers, leading to overcrowding as a result of increased capacity. Thus, there will be a rise in the waiting time of the transport fleet in the loading centers, which in turn increases more the objective function in the second compared to its first part and, consequently, the whole objective function. Hence, optimal capacity is guaranteed by striking a balance between the waiting time and transport, which leads to a minimized objective function.

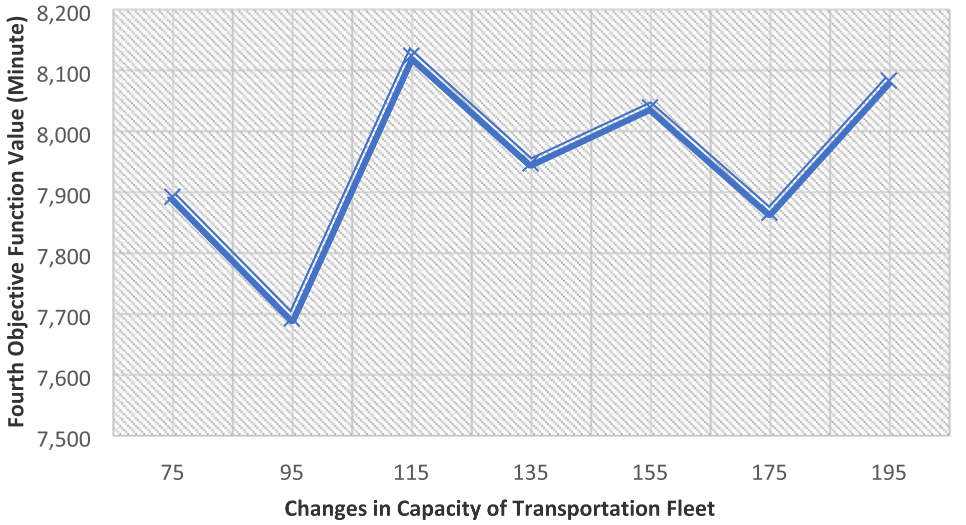


**FIGURE 15** Total waiting time in loading versus capacity of transportation fleet

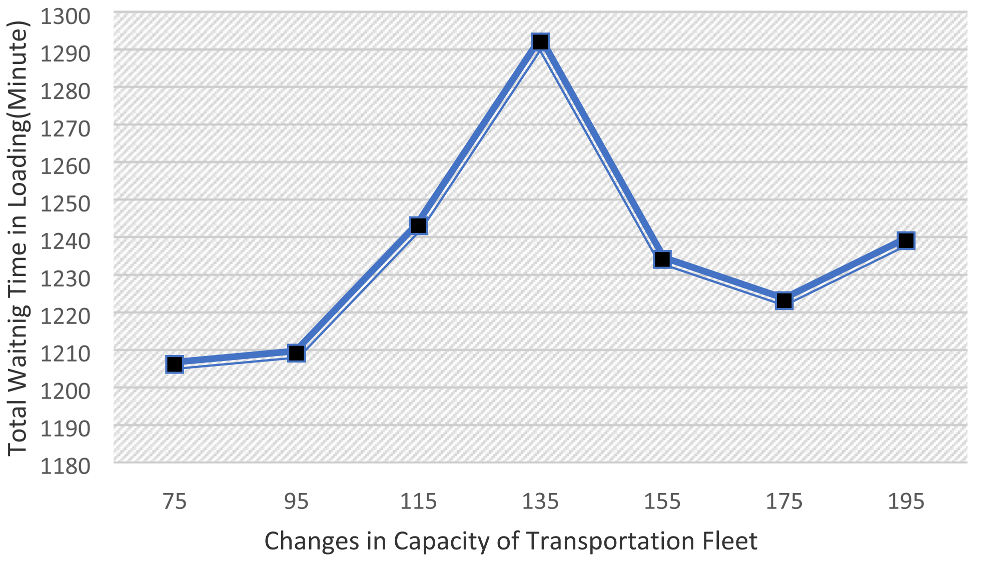


**FIGURE 16** Sensitivity analysis of the fourth objective function by changing the capacity of transportation fleet

## 6 | CONCLUSION

In this article, a mathematical MINLP multiobjective and multiperiod model is proposed based on G/M/S//M queue theory and uncertainty for an agricultural SC case study, for first time. Contrary to other investigations in this area, the proposed model is multiobjective, which focuses on water consumption, energy consumption, and waiting time in the form of independent objective functions. Initially, a definite SC model is proposed that considers the water-energy-food approach. The application of the drip irrigation system, energy-generating solar panels, specifying the amount of harvest, selecting the location of warehouses, waiting and transportation time and the consideration of decay in accordance with transportation distance and temperature are among the decisions of this model. To deal with uncertainty, robust optimization with the HRPP approach is used. This approach is used to solve the models of the agricultural industry in this study, for the first time. In addition, two methods of ε-constraint and LR, are used to solve the problem and the case study due to the better performance of LR method. A sensitivity analysis is performed on each objective function for four of the major parameters, and the most effective ways of improving each function are highlighted. For instance, according to reports from the sensitivity analysis, increasing budgets for equipping greenhouses with drip irrigation is the most effective way to reduce water consumption and waste. Meaning that with a 25% increase in this factor, a 34.7% decrease is reported in water consumption. Followed by increasing the warehouse capacity which improves the reduction in water consumption and waste. The most reliable way to reduce energy consumption is by using more solar panels. Similarly, the drip irrigation system is also able to reduce energy consumption to some extent. Finally, in the case of environmental impacts, the drip irrigation system and warehouse capacity are partially involved in reducing environmental pollution. However, the most effective parameter on this objective function is the use of solar panels for energy generation instead of fossil fuels. Considering the effect of the different parameters that were examined separately for each objective function, in general, it can be said that the drip irrigation parameter has the greatest effect on all objective functions. In second place, solar panels have had the most positive impact on objective functions. These results allow decision makers to know the most effective model parameters.

Although the suggested model tried to address the gaps in the literature, there are still concepts that are worth considering for future investigations. Implementing the level of water and energy consumption for washing and packaging the products in warehouses, the duration in which the agricultural products decay, different transportation vehicles, and the effect of time on the quality of products, can make a significant improvement in the model. In this study, the LR approach has been used to solve the model on a large scale. Future research can include heuristics and meta-heuristics approaches to compare the performance of these approaches. Due to the limitations of this study, solving the model over longer periods of time and conducting more case studies is of great importance in future research.

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## CONFLICTS OF INTEREST

The authors declare that there are no conflict of interests.

## AUTHOR CONTRIBUTIONS

**Komeyl Baghizadeh**: conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (lead); project administration (supporting); resources (equal); software (lead); supervision (equal); validation (equal); visualization (supporting); writing—original draft (equal); writing—review & editing (equal). **Naoufel cheikhrouhou**: investigation (equal); methodology (supporting); project administration (supporting); resources (equal); software (equal); supervision (lead); validation (lead); writing—review & editing (lead). **Kannan Govindan**: data curation (equal); methodology (equal); project administration (equal); supervision (equal); writing—original draft (equal). **Mahboubeh Ziyarati**: conceptualization (equal); data curation (equal); formal analysis (equal); resources (supporting).

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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