Original Research

Optimizing a sustainable inventory-routing problem in tomato agri-chain considering postharvest biological behavior

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Abstract

A new mixed-integer multi-objective model is developed to optimize sustainable inventory-routing decisions in products agri-chain. Economical, social and environmental factors have been integrated in this model. The first objective function considers some traditional terms and novel issues (e.g., postharvest biological behavior of agricultural products), which is related to deviation from ideal quality (customer's dissatisfaction) and the costs of expired products. Because old products have significant environmental impact and require recycling, the reverse logistics framework is used to collect and bring products back to recycling. A function is applied to compute deviation from suitable maturity and customer's dissatisfaction costs. A numerical example is analyzed to indicate the model's applicability by applying the ε-constraint methodology to show the opposite pattern between the two objectives. Remarking the NP-hardness of the presented model, two multi-objective meta-heuristic algorithms, namely the Non-dominated Sorting Genetic Algorithm (NSGA-II) and Multi-Objective Dragonfly Algorithm (MODA) are used to explore near-optimal solutions for medium and large-sized problems. Results show a better performance of the NSGA-II. Furthermore, the sensitivity analysis is presented and explained in four parts to show the trend of the proposed model by fluctuations on important parameters.

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Keywords: Fresh agricultural products; Inventory routing problem; Postharvest biological behavior; Sustainable development.

INTRODUCTION

Growers of perishable crops, frequently face complex organizing problems. Choosing the ideal production method, planting rate, planting and harvesting moment are some of these problems. Furthermore, remarking opposite objective functions can construct more complexity in the field of fresh agronomic production (Ahumada and Villalobos, 2011). Perishability, seasonality, lengthy lead times, short lifetime and parameters uncertainty are some serious points in fresh supply chain management (Hosseini-Motlagh et al., 2021). Agricultural supply chain management has become difficult due to the product's biological postharvest behavior and uncertainty. The quality level of fresh agricultural products is changed exactly after harvest time. The product's fair price is defined according to these fluctuations. These changes are termed as fresh production's postharvest biological behavior (McLaughlin et al., 1999).

The tomato industry is a global and competitive industry with great diversity and innovation (Gary and Tchamitchian, 2001). This product is grown on open fields or greenhouses. There is a great variety in tomato types and fields, cultivation methods, supply chain organizational structure, certification and marketing in the world. Professional tomato production has led to harvesting a large amount of this crop in some countries (Ghezavati et al., 2017). Considering the importance of tomato product, the quality pattern of this product has been noted in this research.

An inventory routing problem (IRP) is a branch of vehicle routing problem (VRP). In IRPs, the inventory and routing policies are noted simultaneously over a specific period (Tavana et al., 2018). Opposite factors such as social-based factors, environmental parameters, and customer dissatisfaction indices should also be considered in addition to the economic aspects of managerial decisions. These considerations lead to further difficulties in the IRPs. These difficulties are more considered in the field of perishable products, which contains critical factors such as expiry moment (Yan et al., 2019). It has been proved by statistics that the agricultural transportation phase leads to a large amount of wastage. As such, a high level of financial losses may happen in this stage (Song and Zhuang, 2017).

Expired products and their wastage can cause various disease and environmental damages. Furthermore, they can cause lots of harm by polluting soil and climate (Onggo et al., 2019). Due to rapid decomposition of expired product's wastage in hot weather, the multiplication of microbes and insects may happen very fast, which can seriously affect the environment (Bottani et al., 2019; Kuhnle and Lanza, 2019).

Helping the producers in the highly critical and competitive fresh agricultural industries is the basic goal of this research. Large finance in technology, facilities, and human resources are required in this industry. Considering the increasingly variable product output and market worth, applying scheduling instruments, such as the one presented in this model, is vital for the long-term profitable planning. The model presented in this paper tries to keep profitability and sustainability for distributors of crops. Also, fair pricing, the postharvest biological behavior of agricultural crops, and inventory routing decisions have been considered in this model. To present a reliable model in the agricultural industry, significant characteristics within the fresh agri-food supply chain are investigated. The model proposed by Ghezavati et al. (2017), has been developed in this research. Also, routing, inventory, and sustainability concepts are incorporated into the former research.

Utomo et al. (2018), analyzed the researches in the field of agri-food supply chain. The reviewed researches used agent-based simulation to run the models. This research has started by investigating the features of the model presented in the literature. The modeling characteristics in the field of agri-food supply chain, have been proposed in this paper. Single echelon supply chain, unprocessed crops, production planning and enterprise decision making are some of mentioned characteristics. Ghezavati et al. (2017) proposed a mathematical model for fresh tomato distribution network. The objective function of this model tends to maximize the total revenue. They considered freshness and ripeness of fresh products to calculate customer's dissatisfaction costs and define fair price. Since the presented model belongs to the NP-hard category, a Bender's decomposition procedure has been applied to handle large-scale points.

Bottani et al. (2019) inquired several reverse logistics patterns considering economic and environmental factors. They appraised their scenarios in canned food losses scope. They executed their model in a zone in Italy. It has been assumed that the wastage are transported from retailers to the depots. They evaluated the suitable level of facilities, the proper route for losses collection, and the entire revenue achieved in recycling process to run an economic assessment. The life cycle evaluation method has been used to execute an environmental assessment. The results demonstrated that recycling the whole losses is a useful environmental method. Bertazzi et al. (2019) applied a novel methodology to solve a multi-depot inventory-routing model. In this model, the routing costs were minimized. In this research, the customers are serviced using multiple depots. Furthermore, the inventory management beside avoiding stockpiles were noted in their research. In this model, a simultaneous equilibrium was instructed among inventory and routing decisions. A three stage meta-heuristic procedure has been used as a solution method.

Abdoli et al. (2017) verified the utility of bi-fuel vehicles. They proposed a mathematical routing problem considering bi-fuel vehicles as an effective approach. They proved that applying bi-fuel vehicles can be noted as an efficient solution for GHG emission reduction. Furthermore, they applied a simulated annealing approach to solve large-sized problems. Rau et al. (2018), presented a green multi-objective multi-period inventory-routing problem. They evaluated the impact of transportation and inventory management on economic and environmental factors. In this research, single and multiple tours, transportation time, capacitated transport and load-related fuel utilization are noted. To achieve the Pareto front, a discrete multi-objective particle swarm optimization and a heuristic optimization method have been applied in this paper. Results show the positive impact of inventory management on costs and emission.

Mousavi et al. (2016) presented a seasonal inventory model concerning the effect of inflation and discount policies. They considered multiple products and multiple periods in their model. Minimization of the sum of inventory costs and the entire holding area were the two objectives of the proposed model. Three meta-heuristic methods have been used to run three various instances and show the capability of the proposed model.

From the review of the accessible literature it is noticeable that no model considers sustainability and biological postharvest behavior of perishable products in Inventory Routing Problems (IRPs) simultaneously. Also, the maturity of fresh products is a significant quality factor and can influence the producer's benefit. Furthermore, applying meta-heuristic methods can be beneficial for solving such an NP-hard problem.

Investigating the impact of transportation process on quality degradation is the main goal of this research. In this paper, a new bi-objective model is extended to plan a fresh agri-chain network in a sustainable IRP environment. A case study of tomatoes is considered for formulating biological patterns. Maximization of total interest is the first goal of the model, while the second objective intends to minimize the rate of accidents to improve social factors. The expense of customer's dissatisfaction and accident extension construct the social phase of proposed model. Remarking the expired product's expense and controlling the GHG release, lead to environmental formation of presented model. Moreover, some agriculture-related points such as safety laws, impartial pricing and postharvest biological behavior have been applied to form the model. Suppliers, retailers and plants, constitute the model distribution network. Also, two linear quality functions have been applied to estimate the deviation from suitable quality and costs of customer's dissatisfaction.

The theoretical context of the investigated issue and mathematical model is developed in the next Section. Then the ε-constraint methodology has been applied to solve a small-sized problem in. Also, solving the presented model by two meta-heuristic algorithms and providing sensitivity analysis are presented in numerical example section. Conclusions and future researches are proposed at the end.

PROBLEM STATEMENT AND MATHEMATICAL MODEL

Lately, consumers of fresh agricultural markets have been applying different solutions to assure the quality of fresh agricultural crops, for instance, harder tomatoes are preferred to riper tomatoes by restaurants (Calvin et al., 2001). Furthermore, there are various types of fresh agricultural products whose agriculture conditions must be considered before they are harvested. Next, considering the primary situation (ripeness) of fresh products, the separation operation is performed. Many quality-related characteristics are defined for fresh products. Freshness and ripeness (maturity) are the two important factors in perishable products supply chain management (Ghezavati et al., 2017).

Fresh agricultural products lose their flavor and nutritional worthiness exactly after being harvested. This process continues so long as the perishability is completed (Oslavd and Strin, 2008). So, the harvesting moment specifies the maximum level of freshness, and the freshness decreases within the shelf life. Quality degradation begins with the emission of a kind of gas that is evaporated just after being harvested. So, the ripeness level of harvested crops and holding statuses like elapsed time and temperature, determine the changes in the initial quality of these crops. The fair price is defined by customer's dissatisfaction from product's state (Lutke Entup et al., 2005).

Separation of products is done according to their quality at harvest time. Freshness and ripeness of agricultural products during transportation and storage processes are captured in the presented model. Maximizing the system total interest (as an economic factor) is the first objective, while minimizing the level of accident (as a social factor) is the second objective. Furthermore, the amount of Green House Gas (GHG) emission (as an environmental factor) is controlled (Minihan and Wu, 2014). Also, the expense of expired products (as an environmental factor) has been considered in the first objective function. Also, customer's dissatisfaction costs with product's quality (as a social factor) are calculated in the first objective function.

The retailers consider crop's freshness. Furthermore, they should receive an acceptable level of maturity. The highest price will be paid for the most qualitative product (with the suitable ripeness level) by retailers. It should be noted that crop's freshness is not important for the plants, while product's ripeness is too significant for them. The highest worth will be paid for products with a suitable level of maturity. Plants try to produce new products such as tomato sauce or canned tomato. It should be noted that, the maximum price paid by customers is more than the maximum price paid by the plants.

As depicted in Figure 1, the distribution network of presented model consists of three elements: (1) supplier that can be considered as a farm or a depot. (2) plants that are production units and (3) customers that are utilization or selling places. The customers and plants receive fresh agricultural production from suppliers. Heterogeneous vehicles are applied to transport the perishable products. Furthermore, in order to reuse the expired products, they are assigned from the customers to the plants. It should be noted that the expired products are recycled and then are used to make new products.

Note that accidents will lead to wastage of a large number of products (i.e., tomato in this paper) and heavy losses for any part of the supply chain. Hence, reducing the level of accidents should be noticed as an important social factor. Furthermore, checking the speed of vehicles and their impact on inventory and routing is necessary as delivery and logistics are the two basic factors of IRPs. So, in this paper, the level of accidents is measured through the speed of vehicles. Also, it is assumed there are various paths between the components of the distribution network with various

Average Traffic Speed (ATS) and Average Vehicle Speed (AVS). To identify the level of the accident in this research, the study of Quimby et al. (1999) is applied. The rate of accident is calculated as follows:

$$RateofAccident = 0.215(\frac{AVS}{ATS})^{7.8} \quad (1)$$

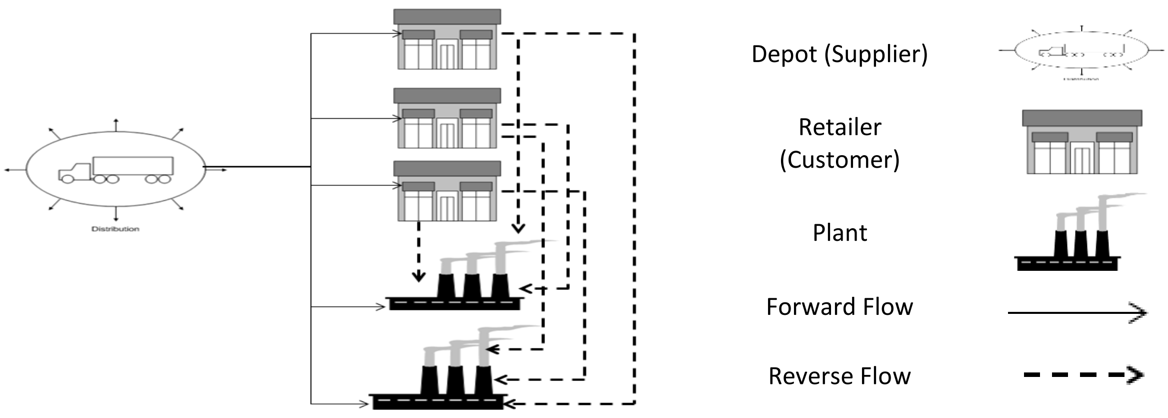


FIGURE 1
DISTRIBUTION NETWORK OF THE MODEL

Remarkably, various factors, such as the hours of the day, climate characteristics, and type of vehicle can affect ATS. Also, the main aim of this research is integrating social factors with IRPs rather than the study of different effective parameters in the accident rate. This factor is calculated by the police reports. Moreover, AVS value is estimated based on the checklists prepared by drivers. Equation (1) is applied to calculate the rate of accidents and reduce the calculation complexity. Note that the number of 0.215 is a fixed number and presented by Quimby et al. (1999).

I. Quality Loss Function of Ripeness

The color, flavor, and the appearance of fresh products are affected by postharvest ripening process (Gary and Tchamitchian, 2001). The achromatic and sleek surface of products shows more maturity, while a less colorful surface is the sign of less maturity. Hence, the suitable maturity (color) is specified by customer's use. The quality changes of fresh crops can be affected by two important factors: (1) the quality (maturity) level at harvesting time (2) the holding condition like temperature and passed time (Tijsken and Evelo, 1994). A function was presented by Hertog et al. (2004) to measure the ripeness over time as presented below:

$$H(t) = H_{max} + \frac{H_{min} + H_{max}}{1 + \left(e^{kt(H_{min} - H_{\max})} (H_{min} - H_0) \Big/ (H_0 - H_{\max})\right)} \quad (2)$$

$H(t)$	The numerical estimation used for crop's ripeness in Hue angle.
t	The time elapsed since harvest time.
$H_{\min}$	The least probable maturity level
$H_{\max}$	The most probable maturity level
H_0	Initial ripeness at the time of harvesting
k	Temperature dependent fixed quantity

The quality level of harvested crops is the main criteria for separating operation. The quality levels must be specified for the harvested crops. The quality level of harvested crops is the main criteria for separating operation. The numerical example of this research is defined on tomato product. The maturity rating presented by USDA (1997), has been applied to determine numeric value related to each maturity level. The six maturity levels and their related numeric estimates are categorized in Table 1. The consumer's satisfaction with the quality defines impartial worth in fresh markets. However, each customer determine a suitable quality interval for received products (Tijskens, and Polderdijk, 1996). As shown in Figure 2, the value of fresh agricultural products is zero when the ripeness of crops is forth of accepted interval and the maximum worth belongs to the crops with the highest level of quality. In this paper, It is supposed that customer's behavior in relation to product status is linear.

TABLE 1
STANDARD MATURITY GROUPING (Saltveit,2005)

Status of maturity	USDA	Hue angle
Mature green (H_{min})	1	115
Breaker	2	83.9
Turning	3	72.85
Pink	4	61.8
Light-red	5	48
Red-ripe	6	41
Over-ripe (H_{max})	+6	37

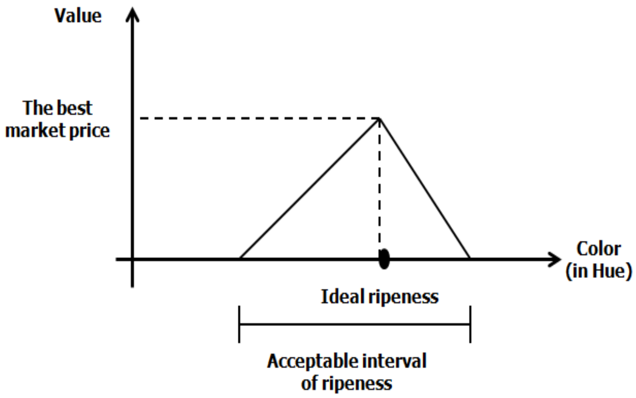


FIGURE 2
LOSS FUNCTION OF DEVIATION FROM OPTIMAL RIPENESS
(Ghezavati et al., 2017)

II. Quality loss function of freshness

The freshness degradation of fresh products starts gradually after being harvested. Microbial motivations and vaporization in the products are the main reasons of degradation. The inappropriate form and structure of fresh yield can result in customer's discontent. It should be noted that perishability and product's maturity are different from each other. As pointed before, the ripening process of products may continue until the customer's acceptable ripeness is achieved. When the ripening process continues, the product's freshness will degrade. So, this process will result in customer's dissatisfaction when freshness is important for the customer. The product's shelf file is defined by its initial quality. Considering pricing courses, the product's price is maximum at harvesting time. Over the time, the product's price will decrease. The product's price will equal to zero when the shelf life is finished.

As depicted in Figure 3, the worth of fresh products degrades linearly because of freshness reduction through time. It should be noted that degradation happens with a decreasing gradient that depends on primary maturity.

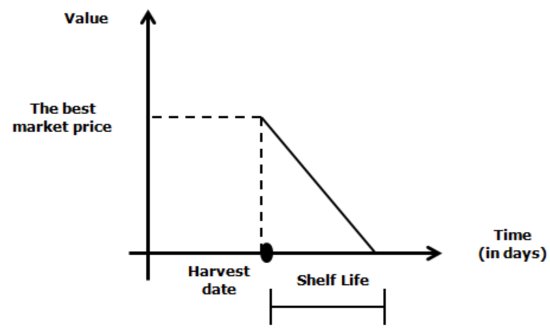


FIGURE 3
LOSS FUNCTION OF REDUCTION IN FRESHNESS
(Ghezavati et al., 2017)

III. Model assumptions

The following assumptions are considered to construct the model:

1. There are different routes between the components of network distribution with different Average Vehicle Speed (AVS) and Average Traffic Speed (ATS).
2. The demand of each period is deterministic.
3. The profit is defined, based on the customer's satisfaction.
4. Customers pay attention to the freshness, but it is not important for the plants.
5. The ordering and expiration costs are not related to the quality of products and are the same for all types of products.
6. The amount of allowed Green House Gas (GHG) output is deterministic.
7. The products are expired just in the place of customers.
8. Holding costs are considered just for customers.
9. Customers pay attention to inventory balance, while capacity constrains have been defined for plants.
10. Delivery is taking place at once.

IV. Indices

$t \in T$	Planning periods
$q \in Q$	Crop's quality level

$i \in DS$	Distribution Centers
$i' \in C$	Customers
$m \in P$	Plants
$v \in V$	Vehicles
$A = i \cup i' \cup m$	Set of nodes (Distribution centers, customers and plants)
$CostEX_{i'mt}$	Expired product's expense transported from customer i' to plant m at time t
AVS_{ijv}	Average vehicle speed of vehicle v between node i and node j; $i, j \in A$
ATS	Average traffic speed
B	Number of customers and plants

V. Parameters

$D_{i'qt}$	Demand from customer i for quality q at time t.
$CapP_m$	Capacity of plant m.
$CapV_v$	Capacity of vehicle v.
$P_{i't}$	Sales value for customer i' in period t.
P_{mt}	Sales value for plant m in period t.
SL_q	Product's shelf life with prime ripeness of q
h	Harvesting time.
$B.RC/P$	Optimum maturity for customer/plant.
$LB.RC/P$	Lowest value of possible ripeness for customer/plant.
Q_q	Quality (ripeness) of products with primal quality q.
c_{ij}	Transportation expense from node i to node j; $i, j \in A$
$OrderSC_{ii'}$	Ordering costs from supplier i to customer i.
$OrderSP_{im}$	Ordering costs from supplier i to plant m.
$\gamma_{i'q}$	Shortage expense related to the crop with primal quality q for customer i'.
FC_v	Fixed transportation cost for vehicle type v
$H_{i'q}$	Holding cost of the product with initial quality q in customer i'
GHG^t_{Total}	Allowable limit for GHG emissions.
GHG_v	Level of GHG produced by vehicle v.
G	A large positive number

VI. Decision Variables

$\mathrm{InC}_{i'qt}$	The inventory level of product with quality q in customer i′ and period t.
$\mathrm{CP}_{i'mqt}$	Expired product's quantity with quality q transported from customer i′ to plant m in period t.
$\mathrm{SC}_{ii'qt}$	Product's quantity with quality q transported from supplier i to customer i′ in period t.
SP_{imqt}	Product's quantity with quality q transported from supplier i to plant m in period t.
$\mathrm{B}_{i'qt}$	Number of backordered products with quality q for customer i′ in period t
x_{ijvt}	1 if point i is serviced exactly after point j by vehicle type v in period t; otherwise 0
$\mathrm{C}_{ii'qt}$	1 if there is any order of products with primary quality q from supplier i to customer i′ in period t; otherwise 0
C_{imqt}	1 if there is any order of products with quality q from supplier i to plant m in period t; otherwise 0
w_{ivt}	Sub-tour elimination variable;
Trans_{vt}	Number of transportations with vehicle v in period t;

VII. Mathematical Model

$$Max\ f_1 = \sum_{i't} P_{i't} \sum_{ii'qt} SC_{ii'qt} + \sum_{mt} P_{mt} \sum_{imqt} SP_{imqt} \quad (3)$$

$$- \sum_{ijvt} c_{ij} x_{ijvt} \quad (4)$$

$$-\sum_{i't} P_{i't} \sum_{ii'tq} SC_{ii'qt} \frac{(t-h)}{SL_q} \quad (5)$$

$$-\sum_{i't} P_{i't} \left(\sum_{ii'q} SC_{ii'qt}. \left[\left(\frac{B.RC - Q_q}{B.RC - LB.RC} \; For\ Q_q < B.RC \right) + \left(\frac{Q_q - B.RC}{UB.RC - B.RC} \; For\ Q_q > B.RC \right) \right] \right) \quad (6)$$

$$-\sum_{mt} P_{mt} \left(\sum_{imq} SP_{imqt}. \left[\left(\frac{B.RP - Q_q}{B.RP - LB.RP} \; For\ Q_q < B.RP, \right) + \left(\frac{Q_q - B.QP}{UB.RP - B.RP} \; For\ Q_q > B.RP \right) \right] \right) \quad (7)$$

$$-\sum_{mqt} H_{i'q} InC_{i'qt} \quad (8)$$

$$-\left(\sum_{ii'qt} OrderSC_{ii'} C_{ii'qt} + \sum_{imqt} OrderSP_{im} C_{imqt} \right) \quad (9)$$

$$-\sum_{i'qt} \gamma_{i'q} B_{i'qt} \quad (10)$$

$$-\sum_{i'mqt} CostEX_{i'mt}.CP_{i'mqt} \quad (11)$$

$$-\sum_{vt} FC_v.Trans_{vt} \quad (12)$$

$$Min\ f_2 = 0.215 \sum_{(i,j)\in A,v,t} \left(\frac{AVS_{ijv}}{ATS} \right)^{7.8} x_{ijvt} Trans_{vt} \quad (13)$$

s.t.

$$InC_{i'qt} - B_{i'qt} = InC_{i'q(t-1)} - D_{i'qt} + \sum_{i} SC_{ii'qt} - \sum_{m} CP_{i'mqt} - B_{i'q(t-1)} \quad \forall i', q, t \quad (14)$$

$$\sum_{iq} SP_{imqt} \le CapP_m \quad \forall m, t \quad (15)$$

$$\sum_{i'q} SC_{ii'qt} + \sum_{mq} SP_{imqt} \le CapV_v Trans_{vt} \quad \forall i, v, t \quad (16)$$

$$\sum_{\substack{i,v \\ i\neq j}} x_{ijvt} = 1 \quad \forall j \in A, t \quad (17)$$

$$\sum_{\substack{j,v \\ i\neq j}} x_{ijvt} = 1 \quad \forall i \in A, t \quad (18)$$

$$W_{ivt} - W_{jvt} + B.x_{ijvt} \le B - 1 \quad \forall (i,j) \in A, v, t \quad (19)$$

$$\sum_{(i,j)\in A} \sum_{v} GHG_v.x_{ijvt} \le GHG^t_{Total} \quad \forall t \quad (20)$$

$$\frac{C_{ii'qt}}{G} \le SC_{ii'qt} \le C_{ii'qt}.G \quad \forall i, i', q, t \quad (21)$$

$$\frac{C_{imqt}}{G} \le SP_{imqt} \le C_{imqt}.G \quad \forall i, i', q, t \quad (22)$$

$$x_{ijvt}, C_{ii'qt}, C_{imqt} \in \{0,1\} \quad (23)$$

$$SC_{ii'qt}, SP_{imqt}, CP_{i'mqt}, InC_{i'qt}, B_{i'qt}, Trans_{vt} \ge 0 \quad (24)$$

$$w_{ivt}\ IntegerVariable \quad (25)$$

The total supply chain's profit is maximized by the first objective function (f_1). The total system's revenue is computed by Term (3). In Term (3) total income is achieved by fresh products sale to the retailers and plants. Variable transportation costs is computed by Term (4). As explained in part 3.1, the customer's dissatisfaction costs from product's freshness is defined by Term (5) as explained in part 3.2. Customer's and plant's dissatisfaction costs from product's maturity are computed by Term (6) and (7) respectively. Term (8) estimates total holding costs. The total ordering cost is shown by term (9). Backordering cost is represented in Term (10). Term (11) calculates the cost of expired products. Fixed transportation cost is calculated by Term (12).

The second objective (f_2) tends to calculate the level of an accident in the proposed network in Term (13), which minimizes the number of accidents as a social factor. According to Equation (1), Term (13) is presented. In this term, the number of accidents is calculated by multiplying the rate of accidents and the quantity of transportations in the presented network. The inventory balance at the customer has been defined by Term (14). This term indicates that the deviation between inventory and shortage level for any quality type in each period equals to the inventory level of previous period plus quantity of product received from the depot minus the total of dispatching crops. Term (15) illustrates that the total amount of shipped products with different quality level (q) from suppliers to each plant in each period shouldn't exceed the capacity of each plant. Constraints (16) guarantee that the load carried by each vehicle in each period, shouldn't be more than the vehicle's capacity. Constraint (17) assures that just one vehicle from one node enters each node in each period. Constraint (18) ensures that just one vehicle leaves each node in each period and it will enter just to one another node. In other words, constraints (17) and (18) assure that just one tour is constructed between customers. Considering MTZ sub-tour elimination constraints, Term (19) defines sub-tour elimination constraints (Miller et al., 1960).

Constraint (20) limits the GHG emission level. Total GHG emission shouldn't be more than the admissible GHG output. Constraint (21) checks that if the customers order any products. If there is any order from a customer, the variable $SC_{ii'qt}$ will have a non-zero value and if there isn't any order, $SC_{ii'qt}$ will equal to zero. Constraint (22) checks that if the plants order any products. If there is any order from a plant, the variable SP_{imqt} will have a non-zero value and if there isn't any order, SP_{imqt} will equal to zero. Constraint (23) is the logical binary requirements on x_{ijvt}, $C_{ii'qt}$, C_{imqt}. Variable x_{ijvt} equals to 1 if vehicle v enters node j after node i in period t. Variable $C_{ii'qt}$ equals to 1 if there is any order from supplier i at the place of customer i' for a product with quality q in period t. Variable C_{imqt} equals to 1 if there is any order from supplier i at the place of plant m for a product with quality q in period t. Constraint (24) is non-negativity integer requirements on $SC_{ii'qt}, SP_{imqt}, CP_{i'mqt}, InC_{i'qt}, B_{i'qt}, Trans_{vt}$. It illustrates that the number of shipped products from suppliers to the plants and customers is a non-negative variable. Also, the level of inventory and shortage are not negative for each customer. Furthermore, the number of transportation for each vehicle is more than or equal to zero. Constraint (25) is defined on sub-tour elimination variable, which is an integer value.

NUMERICAL EXAMPLE

The ε-constraint methodology has been applied to solve a small-sized sample and prove the model's capability. Then two multi-objective meta-heuristic algorithms have been applied to solve medium and large-sized samples. The non-dominated sorting genetic algorithm (NSGA-II) and multi-objective Dragonfly Algorithm (MODA) are the two algorithms.

The example involves five periods and two vehicle types. The agricultural data related to the tomato product is considered in this section. The distribution network includes one supplier (S1), four customers (C1, C2, C3, C4), and two plants (P1, P2). The capacity of plants equals to 4×10^5 for P1 and 4.5×10^5 for P2. The Average Traffic Speed (ATS) equals to 84. The maximum allowed GHG emission equals to 100. The postponement fine equals 5 for C1 and C4, 13 for C2 and 8 for C3.

The values of (upper bound of quality, best quality, lower bound of Quality) equal to (61.8, 48, 41.3) for the customers and (72.85, 61.8, 48) for the plants.

The vehicles related data is presented in Table 2. The value of shelf life and crop's ripeness (calculated by equation 2) are shown in Table 3. Random value for parameters is presented in Table 4.

TABLE 2
VEHICLES RELATED DATA

Vehicle type	Capacity	GHG emission	fixed transportation cost
1	1000	1	20
2	1500	1.9	15

TABLE 3
VALUE OF SHELF LIFE AND CROP'S COLOR

Quality Level	Shelf life	Hue angle
Q1	12	72.85
Q2	10	61.8
Q3	8	48
Q4	5	41

TABLE 4
PARAMETER'S RANDOM QUANTITY

Parameter	Uniform distribution
$OrderSC_{ii'}$	$\sim U(20,100)$
$OrderSP_{im}$	$\sim U(20,100)$
$\gamma_{i'q}$	$\sim U(10,20)$
$H_{i'q}$	$\sim U(10,20)$
$CostEX_{i'mt}$	$\sim U(5,30)$
$P_{i't}$	$\sim U(10,90)$
P_{mt}	$\sim U(30,45)$
$D_{i'qt}$	$\sim U(0,100)$
AVS_{ijv}	$\sim U(70,95)$
c_{ij}	$\sim U(10,90)$
FC_v	$\sim U(10,30)$

I. Solving the proposed example by Ɛ-constraint methodology

To reach the accurate solution of the proposed bi-objective problem, the Ɛ-constraint method is applied. In this method, one of the objectives is optimized and the rest of the objectives are transferred to the constraints section. For more information on this method, refer to (Chankong and Haimes, 1983) and (Cohon, 1978). The Pareto optimal solutions are determined by applying the ε-constraint method as follows:

$$MaxF1$$

s.t.

Constraints (14)-(31)

$$F_2 \le \xi$$

$$LBF_2 \le \xi \le UBF_2$$

where LBF_2 and UBF_2 are the lower and upper limits for F_2. Considering the maximization of the first goal, F_2 is considered to be less than or equal to epsilon value. The model can be solved considering two instances: (1) maximization of F_1 (2) minimization of F_2.

The number of transportations by each vehicle in all periods ($Trans_{vt}$) equals to zero in the second instance to gain the minimum value of accident (zero), which leads to 51186 units cost and no profit is achieved in this instance. Also, the number of products shipped from suppliers to customers and shipped from suppliers to plants equals zero in all periods in this instance to minimize the level of accident.

In the first instance (maximizing F_1), the number of transportations in each period ($Trans_{vt}$) is a non-zero variable, which results in further accident's rate and higher profit. In the first solution instance, the total profit is optimized and equals to 1.54×10^7, while the level of accident (F_2) is high and equals to 324. Solving the second instance leads to accidents level minimization, while the system's total profit has been reduced. The system's total profit diminishes, when the level of accident is minimized. Moreover, the two achieved amounts for F_2 demonstrate limits on F_2.

The efficient frontier of the proposed model is presented in Fig. 4. Also, the evaluation of F_1 and F_2 shows that there is a relationship between the two objective functions. Any of the solution instances with related routing may be selected based on the system designer's policy (value of profit or level of the accident). To reduce the level of accidents from 324 to 0 (zero), the system's total profit is reduced from 1.54×10^7 to -51186 units. This result is completely logical because achieving a higher value of profit will result in a higher rate of accidents. The number of transportations is completely different in the two instances that leads to a massive difference between total profit of solution instances. It determines the opposite behavior between maximizing the total profit and minimizing the level of accident as shown in Figure 4. Consideration of different cases of system's total profit and accidents level will lead to the development of an efficient frontier to be evaluated.

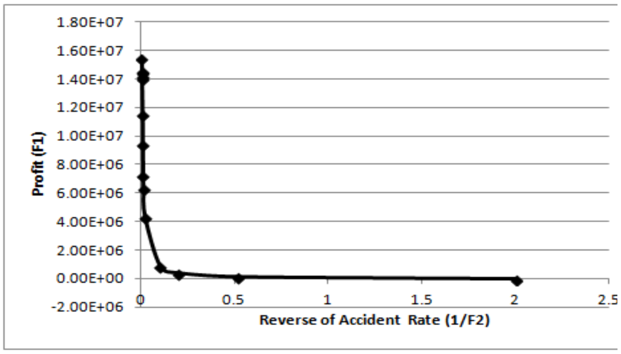


FIGURE 4
EFFICIENT FRONTIER

To analyze the environmental aspects of the presented model and the impact of reverse logistics, the decision variable (CP) for the second Pareto point with $F_1 = 1.45 \times 10^7$ and F_2= 300 is presented in Figure 5. As shown in the diagram, 50 units of expired products, which were expired by the second customer, have been delivered to the first plant to be recycled in the second period. As seen, the quantity of expired products is in the maximum level in the mentioned instance. It should be noted that the amount of crops shipped from supplier to customer is more in the second period which leads to increasing number of recycled products.

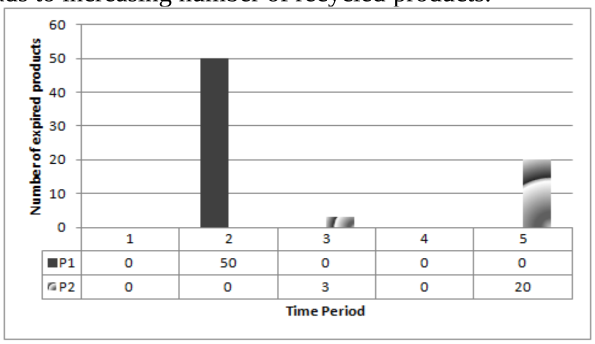


FIGURE 5

NUMBER OF EXPIRED PRODUCTS FOR THE PARETO POINTS

Considering the Pareto point with F_1= 1.15×10[7] and $F_2 = 150$, the routing depicted in Figure 6 is gained. As presented in this figure., the tour formation is different in each period. To reach a higher level of profit, the second vehicle type (V2) has been chosen to visit all points. As is obvious in Table 2, the fixed transportation cost of the second vehicle type is minimum, and selecting this vehicle will result in a lower level of fixed transportation cost and reduction in system total cost which can culminate in an enhanced total profit. Furthermore, the second vehicle type has a higher capacity which leads to lower transportation time, lower fixed transportation cost, as well as a lower level of accident. So, choosing this vehicle can satisfy both the economic and social targets of the presented model.

Furthermore, as depicted in Figure 6, in the first period the first customer ($C1$), with the highest demand is visited. Then, the first plant $(P1)$ is visited where 1356 units of products have been delivered to this plant (SP). Considering the capacity of the vehicle 2, which equals to 1500, uploading 1356 unit of products will lead to less fuel consumption and lower GHG emission. Thus, the environmental goals of the proposed model are captured in this part. Then, the rest of the customers are visited according to their demands.

Also, the level of inventory $(InC_{i'qt})$ for each customer in each period and each quality level for the mentioned point is proposed in Table 5. Furthermore, to analyze the inventory level of products with Q1 quality during all periods for the first customer (C1), which equals to zero (0), constraints (14) has been applied. Since, the level of inventory and shortage cannot be zero simultaneously shortage has taken place in all periods. Also, two states can be considered for the first customer's demand for Q1 quality: (1) the quantity of crops shipped from depot to the retailer $(SC_{ii't})$ equals to zero. (2) the quantity of crops shipped from depot to the retailer $(SC_{ii't})$ is greater than zero, but it does not cover all customer's demand. The final results show that in the first and third period, $(SC_{ii't})$ is a positive number, but it doesn't cover the demand and equals to zero in other periods.

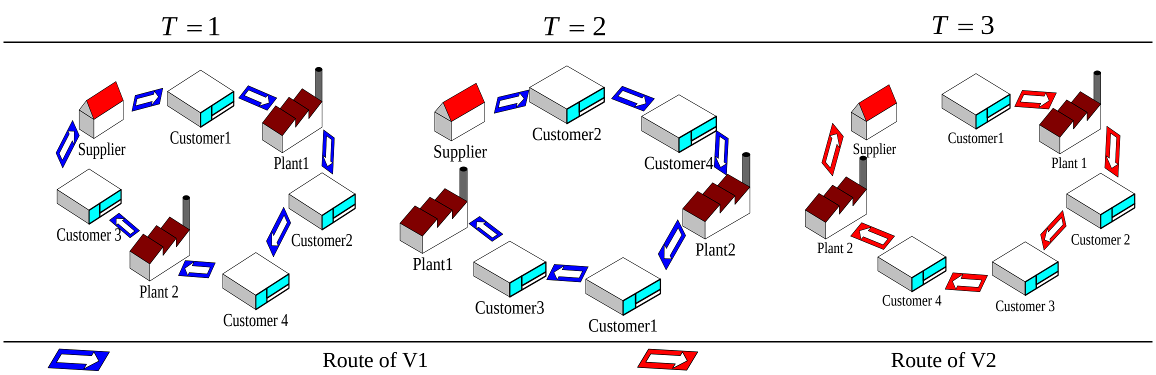


FIGURE 6

ROUTING REPRESENTATION FOR THE PARETO POINT

TABLE 5
INVENTORY LEVEL FOR CUSTOMERS

Index of customer / Quality Level	Time Period					Index of Customer / Quality Level	Time Period				
	1	2	3	4	5		1	2	3	4	5
C1/Q1	0	0	0	0	0	C1/Q1	10	10	0	0	0
C1/Q2	0	0	17	5	5	C1/Q2	4	4	4	2	2
C1/Q3	22	22	29	0	0	C1/Q3	22	22	7	22	22
C1/Q4	0	0	0	0	0	C1/Q4	0	0	0	0	0
C2/Q1	80	80	102	92	92	C2/Q1	20	20	26	4	4
C2/Q2	0	0	52	7	7	C2/Q2	0	0	21	7	7
C2/Q3	5	5	0	0	0	C2/Q3	0	0	0	0	0
C2/Q4	30	30	0	0	0	C2/Q4	2	2	4	0	0

II. Meta-heuristic algorithms

It was shown by Garey and Johnson (1979) that VRP is an NP-hard problem. Moreover, the problem of considering postharvest behavior of agri-food crops in the perishable products supply chain is difficult to be solved for large scale instances (Ghezavati et al.,2017). Integrating the two NP-hard problems has led to a new NP-hard one. Hence, applying meta-heuristic algorithms may be noted as a beneficial method in solving medium and large-sized problems and reducing computational time.

i Solution representation

In any optimization algorithm, defining a suitable representation mode is very significant. The solution representation of this research has been defined in four section as follows:

(1) Ordering plan from customers/ plants: In this part, a three-dimensional matrix is formed (i.e. encoding). Random values in the interval [0,1] construct the matrix. The first dimension of the mentioned matrix determines the index of the supplier, the second dimension determines the index of customers/ plants, and the index of the period is determined by the third dimension of the mentioned matrix. Considering the continuous proceeds of the proposed algorithm, if the random number gets a value in the interval [0,0.5], there is no order from customers/plants. An order takes place from customers/ plants if the random number is generated within the interval [0.5,1]. For example, consider 5 customers for the first period and first supplier. The encoding and decoding procedure is shown as follows:

C1	C2	C3	C4	C5
0.24	0.77	0.02	0.42	0.91

↓

0	1	0	0	1

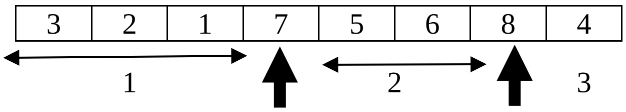
As shown in the above figure customers 2 and 5 have ordered products.

(2) Delivered products from suppliers to customers: The second matrix consists of several genes representing the delivered products from suppliers to customers in each period. In this section, a three-dimensional matrix is formed (i.e., encoding) with random values within the interval [0, max $(D_{i'qt})$]. The first dimension is the index of period. The second dimension is the index of the supplier, while the third one is the index of the customer. The final value of the delivered products to the customers is determined by the algorithm.

(3) Delivered products from suppliers to plants: A three-dimensional matrix with random values in the interval [0, max $(CapacityV_v)$] is created in this section. The first dimension determines the period. The indices of suppliers and plants are determined by the second and third dimensions respectively. The algorithm defines the final value of shipped products from suppliers to plants.

(4) Tour formation: To determine the tour formation, a vector of $1\times(A+V-1)$ has been defined. Each component of this array is related to a random positive integer value in the interval $(0, A+V-1)$. To execute the decoding process, several vehicles are added to the number of nodes. For instance, suppose an example with six nodes and three vehicles. The numbers one to six belong to the nodes. Numbers 7 (first vehicle) and 8 (second vehicle) belong to

the vehicles. Now, suppose that the following array is constructed randomly.



All nodes before number 7 will be visited by the first vehicle. In other words, nodes number 3, 2, and 1 are visited by the first vehicle. The nodes before number eight, are visited with the second vehicle. Finally, the remaining nodes (number 4) will be visited by the third vehicle.

ii Constraint handling

To handle the constraints in this model, two approaches are applied:

1) The first approach is related to the variables defined in solution representation such as x, SC, SP. These variables are defined as the main variables in the solution representation. In each iteration of the algorithm, the value of these variables is calculated. Then, the value of the variables that depends on the mentioned variable (such as inventory level or shortage) is gained (similar to constraint 14). Furthermore, the feasibility related to these constraints is assured by the definition of solution representation. In other words, the solution representation of the main variables is defined such that the constraints related to these variables are feasible. For instance, variable x is defined in a such that the constraints related to routing (constraints (17)-(20)) can gain feasibility. This is completely obvious in tour formation definition in solution representation part.

2) The second approach belongs to the constraints that can not be determined by the variables which were defined in the solution representation. For these types of constraints, a penalty function should be considered. When these constraints aren't satisfied, then a penalty and objective function are added together (such as constraints 15 and 16). In this approach, it should be considered that the objective function and the constraints do not have the same nature. So, each constraint must be multiplied by a particular coefficient. This coefficient tries to omit the difference like constraints which are added to the objective function. This coefficient is of great value. So, the algorithm attempts to gain feasibility and then reduces the value of the objective function. Three tools have been applied to gain the coefficient: (1) use of former researches (2) considering personal experiments (3) trial-and-error to gain the best coefficients for the proposed mathematical model.

iii Non-dominated sorting genetic algorithm II (NSGA-II)

Here, a short description of the employed non-dominated genetic algorithm is presented.

- The initial population is constructed using the method explained in Solution representation.
- The members of the population, which were produced in the last step, are evaluated and classified. Considering the minimization of objective functions, solution x_i dominates solution x_j if $\forall m \in s$ we see $F_m(x_i) \le F_m(x_j)$ and $\exists m \in s$ that $F_m(x_i) \prec F_m(x_j)$. This operation is called a fast non-dominated sorting procedure.
- For the solutions of each non-dominated level, crowding distance is measured.
- In competitive selection, a solution with lower fitness is chosen. If the fitness of two solutions is the same, a solution with more value of crowding distance is selected. And the next generation is constructed.
- The algorithm is stopped when the highest quantity of iterations is achieved.

For more explanation of NSGA-II, refer to (Deb et al., 2002) and (Ding et al., 2018).

iv Multi-objective dragonfly algorithm

An optimization method namely Dragonfly Algorithm was first proposed by Mirjalili (2016). Two main milestones form the Dragonfly's lifecycle: nymph and adult. The nymph stage constitutes the principal part of the dragonfly's lifetime, then they tolerate metamorphism, and the adult phase of their life starts (Thorp and Rogers, 2014). Five factors are defined to consider exploration and exploitation in the mentioned method. The five factors are named separation, alignment, cohesion, attraction, and distraction. The Multi-objective Dragonfly Algorithm (MODA) begins with a random initial population. Then, two vectors namely position and step vectors are determined for each dragonfly. Then, the maximum number of segments and the archive size are defined.

For more explanation on MODA, refer to (Jafari and Bayati, 2017) and Mirjalili (2016).

v Parameters tuning

The Taguchi methodology has been applied to tune the parameters. Initial step vector (SV), the Maximum number of iterations (MI), the maximum number of hyper-spheres (MNHS), and archive size (AS) should be tuned for MODA. Also, population size (N pop), the maximum number of iterations (Max iter), the rate of crossover (Pc), and the rate of mutation (Pm) should be tuned for NSGA-II. For more explanation on the Taguchi method, refer to Mousavi et al. (2016). The parameters tuning for MODA and NSGA-II is presented in Figure 7 and Figure 8 respectively.

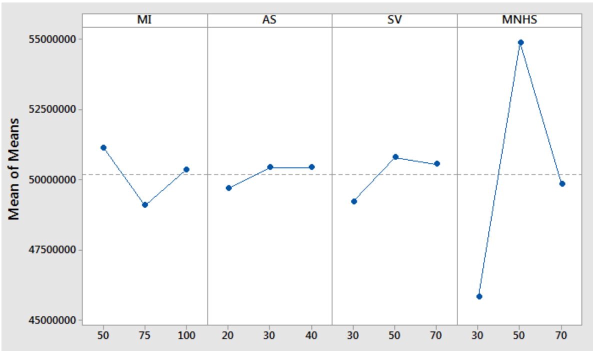


FIGURE 7
ANALYSIS DIAGRAMS OF MODA PARAMETERS TUNING BASED ON TAGUCHI METHOD

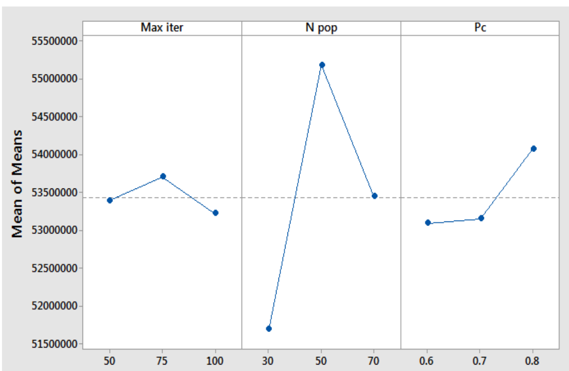


FIGURE 8
ANALYSIS DIAGRAMS OF MODA PARAMETERS TUNING BASED ON TAGUCHI METHOD

vi Comparison metrics

In this part, 20 various examples with different number of suppliers, customers, plants, vehicles, periods and quality levels have been defined to be solved by meta-heuristics algorithms. The capability of the two algorithms is compared applying, quality metric (QM), mean ideal distance (MID), run-time metric (RM), and quantity metric. For more information on these four metrics, refer to Shirzadi et al. (2017) and Tavakkoli-Moghaddam et al. (2011).

The final computing results remarking these four performance indices for the twenty various problems are proposed in Tables 6 to 9.

TABLE 6
VALUE OF QUALITY METRIC

No	Quality Metric (QM)		Δ_1	No	Quality Metric (QM)		Δ_1
	NSGA-II	MODA			NSGA-II	MODA	
1	1	0	1	11	0.38	0.62	-0.24
2	1	0	1	12	0.33	0.67	-0.34
3	1	0	1	13	1	0	1
4	0.8	0.2	0.6	14	1	0	1
5	0.29	0.71	-0.42	15	1	0	1
6	1	0	1	16	1	0	1
7	0.31	0.69	-0.38	17	1	0	1
8	1	0	1	18	1	0	1
9	1	0	1	19	1	0	1
10	0.71	0.29	0.42	20	1	0	1

TABLE 7
VALUE OF MEAN IDEAL DISTANCE

No.	Mean Ideal Distance (MID)		Δ_2	No.	Mean Ideal Distance (MID)		Δ_2
	NSGA-II	MODA			NSGA-II	MODA	
1	0.16	0.84	0.68	11	0.76	0.9	0.13
2	0.023	1.19	1.16	12	1	0.997	-0.003
3	0.016	1.41	1.39	13	0.5	1.12	0.62
4	0.068	0.51	0.44	14	0.05	1.4	1.35
5	0.83	0.98	0.15	15	0.009	1.41	1.4
6	0.013	1.41	1.4	16	0.034	0.83	0.796
7	0.026	0.41	0.38	17	0.12	1.41	1.29
8	0.11	1.41	1.39	18	0.024	1.41	1.386
9	0.015	1.41	1.39	19	0.02	1.2	1.18
10	0.48	0.4	-0.08	20	0.12	1.05	0.93

TABLE 8
VALUE OF QUANTITY METRIC

No.	Quantity metric		Δ_3	No.	Quantity metric		Δ_3
	NSGA-II	MODA			NSGA-II	MODA	
1	11	13	-2	11	10	16	-6
2	11	7	4	12	1	2	-1
3	3	1	2	13	13	13	0
4	16	14	2	14	8	2	6
5	5	12	-7	15	8	1	7
6	11	1	10	16	12	10	2
7	11	13	-2	17	4	1	3
8	12	3	9	18	9	1	8
9	14	1	13	19	11	7	4
10	19	5	14	20	11	10	1

TABLE 9
VALUE OF RUN-TIME METRIC

No.	Run time Metric (RM) NSGA-II	MODA	Δ4	No.	Run time Metric (RM) NSGA-II	MODA	Δ4
1	48	197	149	11	362	536	174
2	153	443	290	12	656	989	332
3	340	840	500	13	92	229	137
4	590	1147	556	14	314	524	209
5	106	292	186	15	718	1077	359
6	323	684	361	16	1165	1379	214
7	513	808	294	17	463	772	308
8	1120	1501	380	18	954	1377	423
9	243	499	256	19	652	1012	360
10	163	295	132	20	548	856	308

vii Statistical hypothesis tests

As it is evident in Table 9, the run time metric of NSGA-II is less than MODA in all 20 examples. For the rest of the metrics, the hypothesis test is done. The confidence level of the statistical hypothesis tests is assumed to be 0.975. The test statistic is calculated by $t = \frac{\Delta-\mu_0}{s/\sqrt{n}}$, $\alpha = 0.025$, and $t_{\alpha,n-1} = 2.063$. The $t = 5.55$, 7.28, and 2.63 for the Quality Metric, Mean Ideal Distance, and Quantity Metric, respectively, and all of them are greater than 2.063. So, results show a better performance of NSGA-II.

III. Sensitivity analysis

In the following part, several instances have been used to investigate the important features of the model and provide managerial sights about the significant attributes of the model. The sensitivity analysis of the proposed model features has been implemented in three parts noticing the data related to Numerical Example part.

Figure 9 displays the effect of temperature and time on the product's quality. In this diagram, changes in hue color (H in ^{o}) of tomato stored at two different temperatures (12 ^{0}C and 15 ^{0}C) versus storage time have been depicted. Applying Equation (2), the values of the Y-axis have been gained. Considering the two trends on this chart, the values related to the product's quality show poor sensitivity to the holding temperature, and the two trends are very similar. Furthermore, passage of time leads to lower product quality and lower hue color considering the values of Table1. Thus, the effect of the time is more obvious than that of temperature on the product's quality. So, passage of time will lead to more quality loss than increasing the temperature, and investing in chilling equipment is not an efficient way to achieve greater revenues.

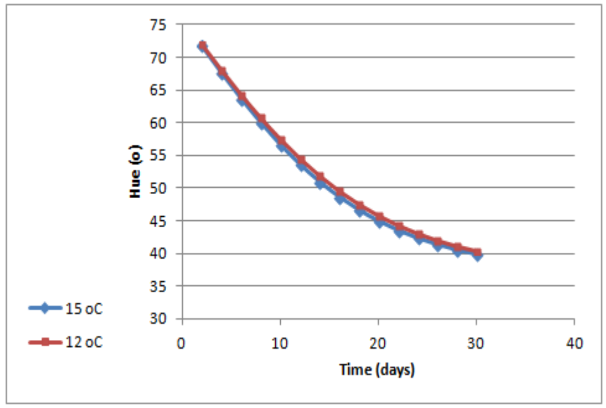


FIGURE 9
CHANGE IN HUE COLOR

Figure 10 reveals the sensitivity of the total profit with variations of plant capacity. Considering constraint (15), increasing the plant's capacity leads to more plant's demand and a higher delivery of products to the plants (SP). Considering the first objective function the total profit which has a direct relation with the quantity of crops delivered from supplier i to plant m will grow. For instance, increasing the capacity of the first plant from 40000 to 44000 and the capacity of the second plant from 45000 to 49500 (10% increase in plant capacity) will result in increasing system total profit from 1.54×10^7 to 1.7×10^7.

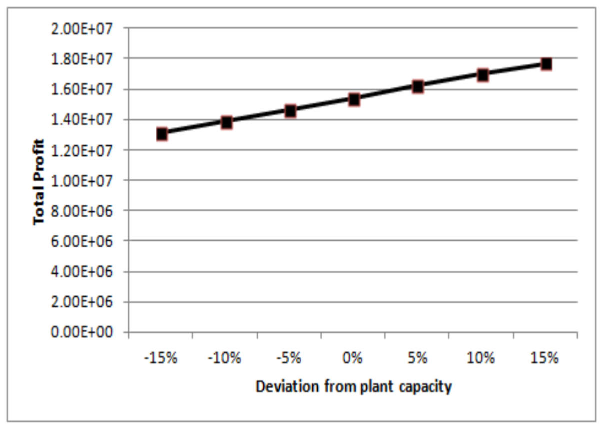


FIGURE 10
PROFIT REGARDING DEVIATION FROM PLANTS CAPACITY

In Figure 11, the effect of deviation from the best quality for the customer on the dissatisfaction costs has been analyzed. As shown in this figure, when the value related to the best quality for the customers ($B.RC$) rises (which means the level of expected freshness by the customer becomes more), the costs related to the maturity decay for the customers which is calculated by Term (7) decrease.

Thus, when the level of best quality rises $(B.RC)$ (or the customer's expectation from the quality extends), the suppliers will try to satisfy the customers and reduce the costs related to the customer's dissatisfaction. It should be noted that the value of $(B.QC)$ can vary only within the accepted interval of ripeness.

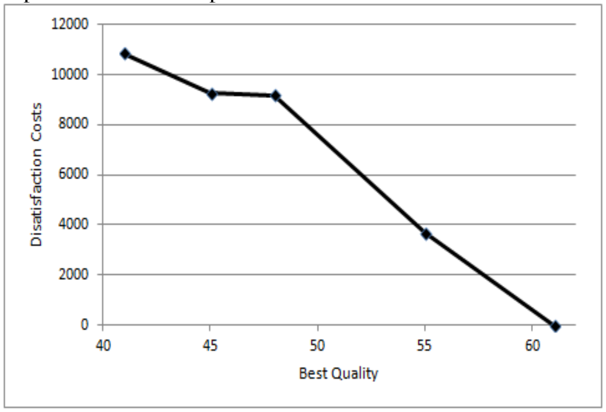


FIGURE 11
DISSATISFACTION COSTS REGARDING VARIATION IN THE BEST QUALITY FOR THE CUSTOMER

MANAGERIAL INSIGHTS

The proposed model can help the producers of fresh agricultural products in the competitive and critical surroundings of the agri-food supply chain. Noticing the variation of product's yield and market price, applying the proposed model is very beneficial for long-term planning. The proposed model tries to protect profitability and sustainability for fresh agricultural products distributors. Consideration of the best-defined quality for each customer to specify the customer's dissatisfaction, inventory, and routing-related decision criteria as well as noticing environmental and social factors can be helpful for the managers.

CONCLUSION

In this paper, a new bi-objective model is proposed to incorporate the distribution of fresh agricultural products and sustainable issues in Inventory Routing Problems (IRPs) for perishable products. Maximizing the whole interest and minimizing the rate of accidents are the model's opposite objectives. The ε-constraint methodology has been applied to achieve exact solutions in small-sized problems and show the conflict between the two objective functions. The results showed that a lower level of accidents results in lower revenue or higher costs. According to the described computational complication, twenty test problems were solved by the two meta-heuristics namely MODA and NSGA-II. The capability of the two algorithms has been analyzed using four metrics. The associated results show a better performance of NSGA-II in comparison with MODA. Also, sensitivity analysis shows that the quality of crops is more sensitive to the holding time than temperature. Furthermore, increasing the plant's capacity can lead to more profit. In the third part of the sensitivity analysis, it has been shown that increasing the best quality considered by the customers in the acceptable interval will result in reducing dissatisfaction costs.

To model the explained problem, the authors tried to notice many operational and process-related factors. Such a comprehensive and full-described model is very applicable to various distribution systems. It should be noted that there were some limitations to this paper. The limited access to real data and ensuring the accuracy of the received data are two of these limitations. Applying other meta-heuristics, like Ant Colony Optimization (ACO), which has a suitable performance on vehicle routing problems, can be interesting for future research. Also, considering uncertainty on other parameters, applying other sub-tour elimination methods, evaluating other social factors, such as employment, health care, labor's effort and stresses, accident-related to fast yielding of process, noticing limitations for customer's dissatisfaction, considering the effect of other factors like brand of products or wholesale price on customer's dissatisfaction and pricing decisions can bring about valuable research.

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