Iranian Journal of Fuzzy Systems
Volume 22, Number 4, (2025), pp. 117-136
Original paper

A bi-phase robust possibilistic model for hub location-routing problem in cold chain logistics of perishable products

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Abstract

In today's competitive markets, determining the optimum distribution centers, delivery routes, and inventory levels is crucial for cold chain logistics of perishable products to reduce costs as well as backorder rate. Meanwhile, a new bi-phase mixed integer non-linear programming model-based robust possibilistic approach is developed by goals of minimizing total costs and reducing the backorder rate for key customers to solve the hub location-routing model for a cold chain of perishable products. To address the issue, the augmented ε-constraint method is considered to construct a single objective model, and the obtained Pareto optimal points are analyzed. Additionally, the robust possibilistic approach is executed to cope with imprecise demand in the presented bi-phase hub location-routing model. To represent the verification and applicability of the proposed approach, a case study on cold chain logistics of perishable products is regarded. Finally, a comparative analysis is considered to compare the obtained results from the proposed approach with real case information. This validation process is defined by schematically reporting the trend comparison results over the entire planning horizon. Moreover, the obtained results represents that the proposed approach can enhance the objective function by reducing the 22% of total costs, improved the backorder level by 24%, the number of deteriorating items decreased by 16.48%, and the inventory levels enhanced by 12.86% regarding the current practice.

Keywords: Hub location-routing problem, robust possibilistic programming model, mixed integer non-linear programming model, fuzzy sets theory, augmented ε-constraint method.

1 Introduction

Nowadays, highly competitive markets are forcing companies to design an efficient and practical supply chain systems. In other words, it is vital for business owners to decrease their costs and improve service levels. Companies need to satisfy their customers in terms of quality, delivery time, price, and so on. Due to the limited lifespan and deteriorating nature of certain products, supply chain of these products is a challenging task [9]. A distribution network design includes facility location problem, inventory management, and vehicle scheduling. Notably, it is crucial to determine the best distribution centers, optimal routes and vehicle, and optimum inventory level throughout the perishable supply chain. In this respect, the recent literature is categorized into three fields, including location-routing problem, inventory-routing problem, and integrated location-inventory-routing problem topics, to appropriately represent the research gap. Finally, a motivation section is provided to reveal the novelties and contributions of the proposed bi-phase robust possibilistic hub location-routing model.

Corresponding Author: H. Gitinavard
Received: December 2024; Revised: May 2025; Accepted: August 2025.
https://doi.org/10.22111/ijfs.2025.50398.8895

1.1 The location-routing problem (LRP)

The LRP problem focuses on locating facilities and determining best routes by considering various goals, including economic, environmental, social, etc. In this respect, many authors have extended the LRP models to solve their problems. Considering the limited capacity of the machines and the unpredictable customer demand, De Maio et. [12] determined the location of cold warehouses and the optimum routes in the dairy industry. Daroudi et al. [11] presented an integrated metaheuristic approach to minimize the latency in LRP in perishable materials. To address the real-world issue, multi-product, multi-period, and uncertain demand have been considered. Golestani et al. [19] developed a bi-objective hub location problem in a cold supply chain, involving numerous perishable materials with different storage temperatures. Musavi and Bozorgi-Amiri [33] developed a multi-objective hub location-vehicle scheduling model with the aim of minimizing the transportation cost, delivery time, spoilage rate, and air emissions in the food supply chain. In addition, Babaee Tirkolaee et al. [43] presented a mixed-integer linear programming (MILP) for LR decisions with a time window in distribution of perishable goods. The aim was to determine the best location of depots and minimize transportation costs.

Furthermore, Wang et al. [45] developed a green location-routing model in fresh agricultural logistics, which reduced total distribution costs and CO2 emissions. A hybrid GA algorithm was utilized to solve the problem. Also, Yaghoubi and Akrami [47] introduced a model to indicate the optimum vehicle routes and distribution points for perishable materials. They proposed an integrated meta-heuristic algorithm to tackle this problem. Besides, Li et al. [25] constructed a bio–objective model to minimize both distribution time and total costs in supply chain of perishable commodities. Some aspects like multi-product, multi-node distribution, and heterogeneous fleets were taken into account in their model. Also, Ji et al. [22] proposed a multi-objective robust optimization methodology for storage warehouses selection problem and distribution path scheduling in supply chain of fresh foods. They considered uncertain demand and finite time horizon in their approach. Chen et al. [8] manipulated an integrated in-store pick-up and delivery problem include perishable products by presenting a two-echelon location–routing model. Rashvand Falari et al.[38] performed a multi-objective locating and routing mathematical model by aims of maximizing customer service, minimizing product distribution time among customers, and minimizing logistics costs and transportation costs for multiple perishable goods.

1.2 The inventory-routing problem (IRP)

The IRP is a strategic distribution issue that aims to determine the minimum fleet size for delivering products from a single depot to customers, considering their usage rate. Meanwhile, some researchers have focused on IRP models to deal with their problems. To solve the problems of freight losses, high transportation costs, and high stock in the perishable grocery market, Song et al. [41] investigated an inventory-routing problem to minimize the total cost in a cold supply chain. Ghasemkhani [16] formulated the IRP for a perishable production and distribution systems to maximize the profit, compute holding cost, and determine vehicle routing. A multi-period, various fleet sizes, time windows, diverse products, and fuzzy variables have been considered in their study. Liu et al. [29] developed a robust optimization model for finding efficient vehicle routes and deliver the highest quality blood to customers at the right time. They also aim to minimize transportation cost, inventory level, and spoilage in the blood supply chain. Besides, Soysal et al. [42] presented a chance-constrained programming model (CCP) for the IRP. Considering demand uncertainty and environmental issues, the proposed model is applied to a real fresh tomato distribution network to minimize total costs, driving time, and energy consumption.

In addition, Azadeh et al. [4] addressed the IRP by considering transshipment for a milk product company. The main objectives were minimizing transportation costs and maximizing the service level to meet customers' needs. The model was solved¬ using the integrated GA-Taguchi algorithm. Besides, Vahdani et al. [44] developed a mathematical model to address a multi-stage IRP for perishable products to maximize profits and minimize delivery time over the distribution system. A meta-heuristic method was presented to solve this problem. Mirzaei and Seifi [32] presented a multi-period non-linear mixed integer programming model to minimize transportation and holding costs in a 2E-IRP for deteriorating products by considering the time window concept.

Furthermore, Rohmer et al. [39] addressed a 2E-IRP for perishable goods intending to minimize transportation and inventory costs. They presented a mixed integer linear formulation and used a two-stage metaheuristic algorithm to solve the problem. Chan et al. [7] introduced a multi-objective optimization model to minimize costs (production, inventory, transportation) and maximize quality level in a real meat supply chain. Also, they minimized CO2 emission and delivery time in the distributing network. In addition, Alvarez et al. [3] studied the IRP for a single perishable good with a fixed lifespan. The branch-and-cut methodology was utilized to address the problem. Additionally, Alkaabneh et al. [2] extended a two-phase meta-heuristic methodology to solve IRP for agriculture products, aiming to minimize the routing costs, inventory costs, traveling time, and harmful emissions. Also, the maximization of total revenue was considered the main objective. Feng et al. [15] presented a novel robust inventory-routing model by aim of minimizing the worst-case mean-conditional value-at-risk attribute. Zhang et al. [49] tailored a multi-type returnable transport closed-loop inventory routing model for perishable food packed. Thereby, He et al. [20] presented a robust counterpart reformulation model based on the benders decomposition-based cutting plane and the duality theorem to solve the perishable product inventory routing problem with imprecise demand. Komijani [24] extended an integrated nonlinear mixed-integer programming model by considering the inventory, routing, and production decisions to solve a green closed-loop supply chain for perishable products with stochastic lifespan.

1.3 The integrated location-inventory-routing problem (ILIRP)

The ILIRP cases are related to some models that combine both aforementioned approaches in which the location of facilities, inventory level, and suitable routes are optimized. However, some authors have focused on the ILIRP issues to consider all aspects of the decision-making levels. Thereby, Liu, Aijun, et al. [28] presented an integrated multi-objective model for the perishable food distribution system, in which facility location problem, inventory management policy, and transportation challenges were incorporated to minimize total costs and improve food freshness. Besides, Li et al. [26] developed a LIRP model to discover optimum routes, distribution center, and inventory level in a cold logistic system. A new version of the PSO algorithm was implemented to achieve the best solution. Hiassat et al. [21] presented a location-inventory-routing (LIR) framework for perishable goods to determine the optimum quantity of warehouse, inventory level, and vehicles travel routes. The genetic algorithm (GA) was implemented to address the problem. In addition, Dai et al. [10] studied a three-level supply chain of deteriorating items to optimize the policies, such as warehouse location, inventory control, ordering costs, and transportation costs. They proposed a hybrid genetic algorithm (HGA) to find solutions. Rafie-Majd et al. [36] introduced a LIRP in a three-level multi-perishable product distribution system by considering a finite time horizon and heterogeneous fleets. They integrated a heuristic algorithm with the Lagrange relaxation method to find a practical solution. Moreover, Saragih et al. [40] extended a heuristic approach utilizing simulated annealing (SA) algorithm to analyze a three-echelon LIRP in a food supply chain. The entities, e.g., stochastic demand, single product, multi retailers, and multi depots, were being considered in their model.

Furthermore, Zandkarimkhani et al. [48] developed a bio-objective MILP methodology for a three-echelon LIRP of perishable pharmaceutical commodities with the objective of minimizing costs and missed demands. To obtain the best solution, they proposed a model based on fuzzy chance-constrained approach. Also, Biuki et al. [6] incorporated location selection, inventory control, and routing planning aspects into the design of a supply network for perishable items. The integration of GA and PSO algorithms was applied to find solutions. Additionally, Rahbari et al. [37] formulated a five-echelon LIRP with deterministic demand for red meat distribution. They introduced a MILP model to minimize total costs, including fixed and variable transportation costs and holding costs. Lingkon et al. [27] developed an integrated multi-objective location-inventory-routing framework for perishable products that provides carbon emissions and product freshness by goals of the maximum freshness of the product as well as lowest economic cost and carbon emissions. Eslamipoor [13] a novel multi-depot three-level location-routing-inventory model to solve the considered problem based on heuristic approach. Zhang et al. [50] a multi-objective two-stage location-inventory-routing programming model for emergency logistics based on multiple reliability under stochastic environment in order to further reduce disaster losses and improve the rescue efficiency.

1.4 Motivations and research gap representation

In today's competitive world, production, storage, and distribution of high-quality perishable products is a challenging task in the food industry. This means that a multi-objective model for location, vehicle routing, and inventory policy plays a vital role in handling these dilemmas. The literature review shows that some scientists have addressed the short-to-mid terms decisions such as inventory and routing planning, while others have proposed solutions for long-term decisions like facility location problems. In addition, some aspects such as one product, single period, homogenous vehicles, and deterministic customer's demand have been considered in the literature studies. However, important factors such as simultaneous pickup and delivery have been overlooked. Nevertheless, our study proposes a multi-objective model to satisfy both short and long-run decisions. Moreover, this research covers real issues, including time window, multiple products, multi-period, uncertain demand, heterogeneous vehicles, and customer periodization. Furthermore, one of the main inspiration is Gitinavard et al. [18]' study that this paper addition to aforementioned features, considered the robust possibilistic programming approach to reach the results with no oscillation and further improvements. In summary, this study offers positive points as given in Table 1. The major contributions of this study are considered includes (1) introducing a non-linear mixed integer programming approach to address the hub-location problem; (2) proposing a new integrated multi-objective non-linear inventory and routing model for a distribution system of perishable products; (3) considering some aspects, including time window, multi-products, heterogeneous vehicles, pickup and delivery, uncertain demand, and customer prioritization; (4) applying robust probabilistic planning to handle the uncertainty of the parameters of the proposed model; (5) implementing the integrated proposed model in a real dairy company to indicate its practicability.

Table 1: Comparison of model characteristics in the literature

Author(s)	Decision-making level				Model's characteristics						
	Strategic	Tactical	Operational	Customers' prioritization	Multi-product	Multi-period	Heterogeneous fleet	Pickup and delivery	Time window	Demand uncertainty	Multi-objective
Hiassat et al. [21]	✓		✓		✓				✓		
Azadeh et al. [4]		✓			✓	✓			✓	✓	
Vahdani et al. [44]		✓	✓		✓	✓			✓		✓
Wang et al. [45]	✓		✓		✓						
Rafie-Majd et al. [36]	✓	✓	✓		✓	✓	✓		✓	✓	
Babaee Tirkolaee et al. [43]	✓		✓		✓		✓		✓		
Saragih et al. [40]	✓	✓	✓								✓
Rohmer et al. [39]		✓	✓		✓				✓		
Alvarez et al. [3]		✓	✓			✓					
Ji et al. [22]	✓		✓				✓		✓	✓	
Zandkarimkhani et al. [48]	✓	✓	✓		✓	✓	✓		✓	✓	✓
Biuki et al. [6]	✓	✓			✓	✓			✓	✓	
Fattahi et al. [14]		✓	✓						✓	✓	
Majidi et al. [30]		✓	✓		✓				✓	✓	
Barma et al. [5]		✓	✓		✓		✓		✓		✓
This article	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The structure of this study is organized as follows: in Section 2, the problem description is prepared to reveal the considered aspects of the hub location-routing problem. In Section 3, the proposed bi-phase hub location-routing model based on both strategic and tactical levels is formulated. In addition, the solution approach by preparing a linearization methodology, an augmented -constraint method, and a robust possibilistic programming model is explained in Section 4. Moreover, in Section 5, a case study about the cold chain logistics of perishable products is defined, and the proposed approach is implemented to represent the verification of this study. In Section 6, the validation process is designed by comparing the obtained results from the proposed approach with real case information. Finally, some concluding remarks and future research suggestions are discussed in Section 7.

2 Problem definition

Consider a graph (N, A) consisting of nodes set $N = (1, ..., N)$ and arcs set $A = ((i, j)/i, j \in \mathbb{N}, i \neq j)$. In this network, node O denotes the depot and nodes $(N/\{0\})$ represents each customer. The customers' demand for each perishable product (d^p_{ir}) is determined at the beginning of each period. Then, according to market demand, the distribution centers (DC) presented a list of products to factories (g^p_{jfr}). Due to the dispersion of customers, the right warehouse location is of great importance. Also, the inventory level should be controlled regarding the predetermined capacity of distribution centers (θ_j). The backorder quantity is determined throughout the factories-distribution centers-customers (FDCC) path based on the perishability rate of products. In other words, the backorder quantity from the factory as well as from DCs is specified. Hence, the quantity of products is delivered to DCs and customers considering the backorder rate. A specific time window $[w^{LP}_i, w^{UP}_i]$ is utilized to ensure that customers receive their needs at the right time. In addition, the customers are prioritized based on purchase quantity, distance from the depot, and purchasing history. However, the schematic representation of the hub location-routing problem is depicted in Figure 1.

3 Proposed bi-phase hub location-routing model for perishable products

In this section, the proposed two-phase approach is divided into two decision levels, which are strategic and tactical. Herein, as indicated in Figure 2, the novel hub location model is presented at the strategic level, and the warehousing and routing model is proposed at the tactical level.

3.1 Assumptions

In this section, some assumptions are provided to facilitate the proposed bi-phase hub location-routing model as follows:

1. The customer prioritization depends on purchase amount, purchase frequency, and the customer's distance from the depot.

2. Each customer is assigned a time window and a service rate

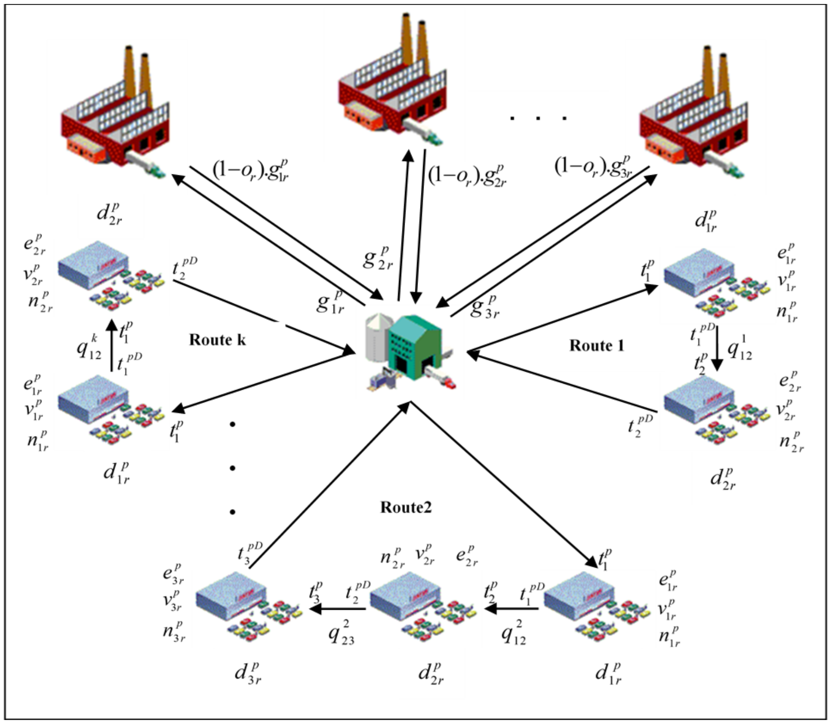

Figure 1: The schematic representation of hub location-inventory-routing problem

3. Partial backorder is permitted.
4. The distribution system has one depot.
5. The customer's demand is uncertain
6. The transportation fleet includes vehicles with various capacities; hence, there are heterogeneous fleets.
7. The supply chain considers multi-perishable product, multi-period, and multi-echelon, i.e., factories, distribution centers, and customers.
8. According to historical data and experts' opinions, customer demand is calculated in different periods
9. Considering the pickup and delivery of products to/from customers.
10. A medium-size real-case study is considered to represent the the effectiveness and practicability of the proposed model.

3.2 Notations

In this section, the proposed hub location model is presented to determine the most suitable location for the hub. In this respect, sets, parameters, and variables are defined as follows:

3.2.1 sets

i, j, l	set of customers $(i, j, l = 1, ..., N)$
f	set of manufacturers of perishable products $(f = 1, 2, ..., F)$
k	set of vehicles $(k = 1, 2, ..., K)$
r	set of products $(r = 1, 2, ..., R)$
p	set of periods $(p = 1, 2, ..., P)$

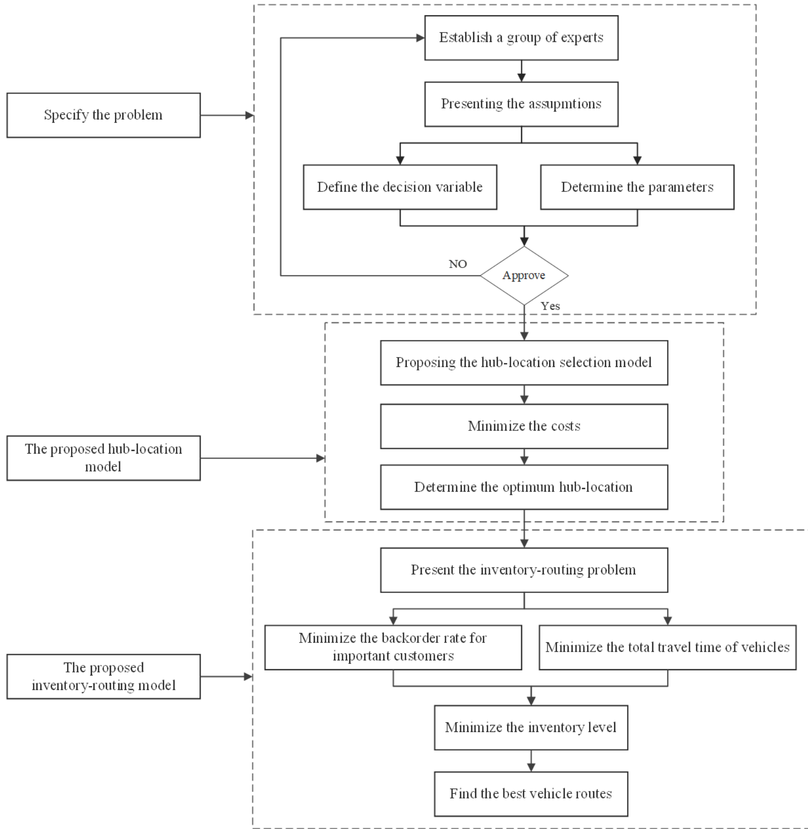

Figure 2: Hierarchical procedure of the proposed model

3.2.2 Parameters

d_{ir}^{p}	Demand of customer i for perishable dairy product r in period p
q_{ij}^{k}	Duration time between customers i and j by vehicle k
s_i	Service rate of customer i
Q^k	Capacity of vehicle k
θ_j	Capacity of located hub j
w_i^{Lp}	Lower bound of time window for customer i in period p
w_i^{Up}	Upper bound of time window for customer i in period p
C_r	Amount of vehicle capacity occupied by a unit of product r
Ψ_i	Relative importance of customer i
u_r	Perishable rate for product r
e_{ir}^{p}	Quantity of spoiled product r from customer i in period p
o_r	Perished rate of product r in customers
C_{fj}^{Fp}	Cost of delivered product from producer f to hub j within period p
C_{jir}^{0}	Shipment cost of product r from hub j to customer i
m_r	Maximum number of period that product r could be storage in the depot
EX_r	Expired period of product r

3.2.3 Variables

x_{ij}^{kp}	1, if the link from customer i to j is visited by vehicle k in period p; 0, otherwise;
Y_{ij}	1, if customer i is assigned to located hub j; 0, otherwise;
t_i^p	Delivery start time at customer i in period p
t_i^{Dp}	Departure time from customer i in period p
g_{ifr}^p	Amount of ordered product r from located hub j to producer f in period p
h_r^p	Amount of inventory of product r in period p
b_r^p	Backorder quantity for product r during period p
v_{ir}^p	Quantity of delivered product r to customer i in period p
n_{ir}^p	Quantity of picked up spoiled product r from customer i in period p

3.3 Strategic level formulation

The proposed mixed integer non-linear programming (MINLP) model for locating the most appropriate candidate hub is presented as follows:

$$Z = \min \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{f=1}^{F}\sum_{i=1}^{N}\sum_{j=1}^{N}\Big(Y_{jj}(C_{fjr}^{Fp} + C_{jir}^{0} v_{ir}^{p})\Big), \tag{1}$$

S.t.:

$$\sum_j Y_{ij} = 1, \quad \forall i, \tag{2}$$

$$\sum_j Y_{fj} = 1, \quad \forall f, \tag{3}$$

$$\sum_{j=1}^{N} Y_{jj} = P, \tag{4}$$

$$Y_{ij} \leq Y_{jj}, \quad \forall i, j, \tag{5}$$

$$Y_{fj} \leq Y_{jj}, \quad \forall f, j, \tag{6}$$

$$\sum_{p'=p}^{p+m_r}\sum_{i=1}^{N} d_{ir}^{p} \geq g_{jfr}^{p} Y_{jj}, \quad \forall j, f, r, p, \tag{7}$$

$$\sum_{f=1}^{F}\Big[g_{jfr}^{1} Y_{jj}\Big] = \sum_{i=1}^{N} d_{ir}^{1} + b_r^0 - h_r^0, \quad \forall j, r, \tag{8}$$

$$\sum_{f=1}^{F}\Big[g_{jfr}^{p} Y_{jj}\Big] + h_r^{p-1} - b_r^{p-1} = \sum_{i=1}^{N} d_{ir}^{p} + b_r^p - h_r^p, \quad \forall j, r, p, \tag{9}$$

$$\sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{i=1}^{N}\sum_{j=1}^{N}\Big[C_r v_{ir}^{p} Y_{jj}\Big] \leq \sum_{j=1}^{N}\Big[Y_{jj}\theta_j\Big], \tag{10}$$

$$\sum_{i=1}^{N} v_{ir}^{1} = (1-o_r)\cdot\sum_{f=1}^{F}\Big[g_{jfr}^{1} Y_{jj}\Big] - b_r^1, \quad \forall j, r, \tag{11}$$

$$\sum_{i=1}^{N} v_{ir}^{p} = (1-o_r)\cdot\sum_{f=1}^{F} g_{jfr}^{p} + h_r^{p-1} - b_r^p, \quad \forall j, r, p \geq 2, \tag{12}$$

$$h_r^1 = b_r^P = h_r^P = 0, \quad \forall r, \tag{13}$$

$$v_{ir}^{1} \leq d_{ir}^{1}, \quad \forall r, i, \tag{14}$$

$$v_{ir}^{p} \leq d_{ir}^{p} + \sum_{p'=1}^{p-1} \left(d_{ir}^{p'} - v_{ir}^{p'} \right), \quad \forall r, i, p \geq 2, \tag{15}$$

$$\sum_{p=1}^{P} v_{ir}^{p} = \sum_{p=1}^{P} d_{ir}^{p}, \quad \forall r, i, \tag{16}$$

$$v_{ir}^{p},\, g_{jfr}^{p},\, h_{r}^{p},\, b_{r}^{p} \in \text{Integer}, \quad Y_{ij} \in \text{Binary}. \tag{17}$$

The objective function (1) aims to minimize the cost of transporting perishable products from factories to distribution centers as well as from distribution centers to customers. Constraints (2) and (3) state that all factories and customers are assigned to merely one hub center. Constraint (4) ensures that P hub is located among the networks' nodes. Constraints (5) and (6) indicate when a node is chosen as a hub, the remaining nodes are considered as factories and customers. Constraints (7) guarantee that the ordered products are less than the demands of customers in each period. Constraints (8) and (9) are the balance equations for the hub center. Constraints (10) imply capacity constraints of the located distribution centers. Constraints (11)-(13) determine the quantity of products delivered to DCs and customers. Constraints (14) and (15) ensure that extra delivery of products is not permitted in located DCs. Constraints (13) and (16) guarantee that all customer demands must be met over the whole planning period. Constraint (17) shows the binary and integer variables.

3.4 Tactical level formulation

In this section, the proposed integrated warehousing and routing model is presented. In this respect, the proposed MINLP model for integrated warehousing and routing problem is given as follows:

$$Z_1 = \min \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{r=1}^{R} \sum_{i=1}^{N} \sum_{j=1}^{N} \left[x_{ij}^{kp} \left(s_i (v_{ir}^{p} + n_{ir}^{p}) + q_{ij}^{k} \right) \right], \tag{18}$$

$$Z_2 = \min \sum_{p=1}^{P} \sum_{r=1}^{R} \sum_{i=1}^{N} \left[\psi_i (d_{ir}^{p} - v_{ir}^{p}) \right], \tag{19}$$

S.t.:

$$x_{ii}^{kp} = 0, \qquad \forall i, k, p, \tag{20}$$

$$\sum_{k=1}^{K} \left[\sum_{\substack{i=0 \\ i \neq j}}^{N} x_{ij}^{kp} \right] = 1, \qquad \forall j \neq 0,\, p, \tag{21}$$

$$\sum_{j=1}^{N} x_{0j}^{kp} = 1, \qquad \forall k, p, \tag{22}$$

$$\sum_{i=1}^{N} x_{i0}^{kp} = 1, \qquad \forall k, p, \tag{23}$$

$$\sum_{j=1}^{N} x_{jl}^{kp} - \sum_{i=1}^{N} x_{li}^{kp} = 0, \qquad \forall k, p, l, \tag{24}$$

$$t_i^{Dp} = t_i^{p} + \sum_{r=1}^{R} \left[s_i \cdot (v_{ir}^{p} + n_{ir}^{p}) \right], \qquad \forall i, p, \tag{25}$$

$$t_0^{Dp} = 0, \qquad \forall p, \tag{26}$$

$$t_j^{p} = \sum_{i=1}^{N-1} \sum_{k=1}^{K} x_{ij}^{kp} \, (t_i^{Dp} + q_{ij}^{k}), \qquad \forall j, p, \tag{27}$$

$$\sum_{\substack{i=0\\ i\neq j}}^{N} x_{ij}^{kp} w_i^{Lp} \leq t_j^p \leq \sum_{\substack{i=0\\ i\neq j}}^{N} x_{ij}^{kp} w_i^{Up}, \qquad \forall j,k,p, \tag{28}$$

$$\sum_{i=0}^{N}\sum_{j=1}^{N}\sum_{r=1}^{R} x_{ij}^{kp} v_{jr}^{p} C_r - \sum_{i=0}^{N}\sum_{r=1}^{R} x_{ij}^{kp} v_{jr}^{p} C_r + \sum_{i=0}^{N}\sum_{r=1}^{R} x_{ij}^{kp} n_{jr}^{p} C_r \leq Q^k, \qquad \forall k, j\geq 1, p, \tag{29}$$

$$\sum_{p=2}^{P} n_{ir}^{p} - \sum_{p=2}^{P} e_{ir}^{p} = 0, \qquad \forall r,i, \tag{30}$$

$$g_{0fr}^{p} \leq \sum_{p'=p}^{p+m_r}\sum_{i=1}^{N} d_{ir}^{p}, \qquad \forall f,r,p, \tag{31}$$

$$\sum_{f=1}^{F} g_{0fr}^{1} = \sum_{i=1}^{N} d_{ir}^{1} - h_r^0 + b_r^0, \qquad \forall r, \tag{32}$$

$$\sum_{f=1}^{F} g_{0fr}^{p} + h_r^{p-1} - b_r^{p-1} = \sum_{i=1}^{N} d_{ir}^{p} - h_r^p + b_r^p, \qquad \forall r,p, \tag{33}$$

$$\sum_{i=1}^{N} v_{ir}^{1} = (1-o_r)\sum_{f=1}^{F} g_{0fr}^{1} - b_r^1, \qquad \forall r, \tag{34}$$

$$\sum_{i=1}^{N} v_{ir}^{p} = (1-o_r)\sum_{f=1}^{F} g_{0fr}^{p} - b_r^p + h_r^{(p-1)}, \qquad \forall r,\ p\geq 2, \tag{35}$$

$$h_r^1 = b_r^P = h_r^P = 0, \qquad \forall r, \tag{36}$$

$$\sum_{p=1}^{P} v_{ir}^{p} = \sum_{p=1}^{P} d_{ir}^{p}, \qquad \forall r,i, \tag{37}$$

$$v_{ir}^{p} \leq d_{ir}^{p} + \sum_{p'=1}^{p-1}\left(d_{ir}^{p'} - v_{ir}^{p'}\right), \qquad \forall r,i,\ p\geq 2, \tag{38}$$

$$v_{ir}^{1} \leq d_{ir}^{1}, \qquad \forall r,i, \tag{39}$$

$$t_i^p,\ t_i^{Dp},\ g_{jfr}^{p},\ h_r^p,\ b_r^p,\ v_{ir}^{p},\ n_{ir}^{p} \in \text{Integer}, \qquad x_{ij}^{kp} \in \text{Binary}. \tag{40}$$

The objective function (18) tries to minimize the total travel time of vehicles from manufacturing centers to distribution centers and from DCs to customers. To increase the satisfaction level of customers, objective function (19) aims to minimize the deviation of delivered commodities for prominent customers. Constraint (20) ensures that vehicles move from one customer to another. Constraint (21) guarantees that each customer is served only once. Constraints (22)-(24) imply the balance of workload. The movement time from one customer to another is determined through the constraints (25) and (26). Constraint (27) specifies the delivery time to the customer. Constraints (28) state that every customer must be served in a limited time window. Constraints (29) indicate the vehicle capacity regarding delivery and pick up of products and spoiled commodities, respectively. Constraint (30) declares that spoiled products must be collected throughout the planning horizon. Constraints (31) assert that ordered products from depot to each factory must never surpass the total demand for every item. Constraints (32) and (33) are the balance equations for the depot. Constraints (34)-(36) determine the amounts of products delivered to DCs and customers. Constraint (37) assures that every customer's demand must be satisfied throughout the entire planning horizon. Constraints (38) and (39) ensure that extra delivery of products is not permitted in located DCs. Finally, Constraint (38) indicates the decision variable types.

4 Solution approaches

In the proposed approach, we face some challenges, such as non-linear model, multi-objective optimization, and uncertain parameters. To address these concerns, three phases have been developed. At first, A compact form of the inventory-routing problem is presented. Similarly, the hub location problem can be formulated using the same structure. The proposed compact IRP model is given in the ensuing lines.

$$\begin{aligned}
\text{Model I}\quad & f_1 : \min Z_1 = C_1XY + C_2X, \\
& f_2 : \min Z_2 = \tilde{C}_3Y, \\
\text{s.t.:}\quad & \\
& A_1X = B_1, \\
& A_2X + R_1Y \le B_2, \\
& R_2Y = \tilde{B}_3, \\
& P_1XY + A_3X + R_3Y = 0, \\
& P_2XY \le B_4, \\
& R_4Y \le \tilde{B}_5, \\
& Y \in \{0, 1\}, \quad X \in \mathbb{Z}.
\end{aligned}$$

4.1 Linearization

Since the constraints of the model I are non-linear. In this regard, consider Z as an auxiliary variable ($Z = X * Y$) in which X and Y are binary and positive variables, respectively. To transform the non-linear model into a linear one, the below constraints must be incorporated into the original model.

$$\begin{aligned}
& Z \ge Y - M(1 - X), \\
& Z \le Y + M(1 - X), \\
& Z \le MX, \\
& X \in \{0, 1\}, \\
& Y, Z \in \text{integer}.
\end{aligned}$$

Here the M represents a large positive number.

4.2 Robust possibilistic programming approach

In the real-world, the lack of historical data and knowledge leads to ambiguous circumstances. In this study, customers' demand and transportation costs are considered uncertain parameters that the robust possibilistic programming (RPP) model could reduce the existing uncertainty. Meanwhile, the RPP is first introduced by Pishvaee et al. [34] and developed based on CCP that is a credible possibilistic programming approach and relies on strong mathematical concepts such as possibility and necessity measures and the expected value of a fuzzy number. This feature could help the experts to control the constraints' satisfactions confidence level besides supporting various kinds of fuzzy numbers such as trapezoidal and triangular forms. Although, triangular possibility distributions is a special case of trapezoidal possibility distributions, Pishvaee et al. [34] considered trapezoidal possibility distributions for modeling imprecise parameters by defining four prominent points. Consequently, we have preserved the primary structure of the proposed RPP and we utilized the trapezoidal fuzzy numbers instead of other membership functions such as triangular ones. To deal with inherent uncertainty effectively, the basic possibilistic chance-constrained programming (BPCC) is stated as follows [35]:

$$
\begin{aligned}
\text{Model II} \quad & \min E(Z_i) = E(c)x + E(f)y, \\
\text{s.t.:} \quad & A_1 x = B_1, \\
& A_2 x + R_1 y \le B_2, \\
& \text{Nec}(R_2 y = \tilde{B}_2) \ge \alpha, \\
& P_1 z + A_3 x + R_3 y = 0, \\
& P_2 z \le B_4, \\
& \text{Nec}(R_4 y \le \tilde{B}_5) \ge \beta, \\
& z \ge y - M(1-x), \\
& z \le y + M(1-x), \\
& z \le Mx, \\
& y \in \{0,1\}, \quad x,\ z \in \text{Integer}.
\end{aligned}
$$

Noteworthy, the trapezoidal possibility distribution is utilized for the imprecise parameters of the proposed model. However, the equivalent crisp formulation of the aforementioned model can be given as:

$$
\begin{aligned}
\text{Model III} \quad & \min E(Z_2) = \left(\frac{c_3(1) + c_3(2) + c_3(3) + c_3(4)}{4}\right) y, \\
& Z_1 = \min c_1 z + c_2 x, \\
\text{s.t.:} \quad & A_1 x = B_1, \\
& A_2 x + R_1 y \le B_2, \\
& R_2 y \le \frac{\alpha}{2} B_2(3) + (1 - \frac{\alpha}{2}) B_2(4), \\
& R_2 y \ge \frac{\alpha}{2} B_2(2) + (1 - \frac{\alpha}{2}) B_2(1), \\
& A_3 x + P_1 z + R_3 y = 0, \\
& P_2 z \le B_4, \\
& R_4 y \le B_5(2)(1-\beta) + B_5(1)\beta, \\
& z \ge y - M(1-x), \\
& z \le y + M(1-x), \\
& z \le Mx, \\
& y \in \{0,1\}, \quad x, z \in \text{Integer}.
\end{aligned}
$$

Notably, the confidence level should be considered more than 0.5 ($e.g., \alpha, \beta > 0.5$) in the chance constraints. A minimum confidence level, as a proper safety margin, is set by the decision maker (DM) to satisfy chance constraints.

4.3 Multi-objective programming

In this section, the augmented -constraint method is utilized [31] to cope with the multi-objective nature of the proposed approach. This technique involves optimizing one objective while the remaining objective functions are considered as constraints. To find optimum Pareto solutions, the following relations are given as:

$$
\begin{aligned}
\text{Model IV} \quad & \max \left(f_1(x) + \delta\left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \cdots + \frac{s_p}{r_p}\right)\right), \\
& f_2(x) - s_2 = \varepsilon_2, \\
& f_3(x) - s_3 = \varepsilon_3, \\
& \vdots \\
& f_p(x) - s_p = \varepsilon_p, \\
& x \in S, \qquad s_i \in \mathbb{R}^+.
\end{aligned}
$$

In which $\epsilon \in [10^{-6}, 10^{-3}]$.

5 Case study

5.1 Case representation

To prove the effectiveness and practicability of the proposed model, a real case study of the dairy manufacturer is adopted from Gitinavard et al. [17]. This company is one of the reputable dairy manufacturers producing various products in Iranian and international markets. Its customers are restaurants, supermarkets, hypermarkets, schools, organizations, and so on. In this regard, the geographical area of this study is implemented in the north of Iran. Four investigated cities are considered, and 26 main customers are defined based on experts' opinions. The customers' needs are met by three types of vehicles with a capacity of 2500, 3000, and 3500 units, respectively. Based on empirical evidence, the average travel time between two customers within a city, spans from 1 to 9 minutes. Also, the average travel time between each city is 30 minutes. When delivering new products, the vehicles must collect the spoiled products from the previous period. The pickup time for each deteriorated product is 20 seconds. Regarding the perishability of the products, the shipping time from the manufacturer to the warehouse and from depots to customers is of great importance. Owing to the lack of sufficient information about the quantity of required products, weather conditions, traffic, etc., the transportation cost from the factory to warehouses is uncertain. Each customer is prioritized based on monthly purchase quantity, purchase frequency, the distance from the depot, and so on. As shown in Table 2, Ψ_i' and Ψ_i represents the relative and normalized weights of customers, respectively. The customers 3, 13, and 22 have high priority. The demand for products is determined daily and may change during the planning horizon. Hence, to deal with uncertainty of demand, trapezoidal distribution [46] is utilized to represent the quantity of demands that is adopted from [18].

Table 2: The customers' prioritization

Customer i	ψ_i	ψ_i'	**Customer** i	ψ_i	ψ_i'
1	0.3	0.018	14	0.5	0.030
2	0.6	0.037	15	0.5	0.030
3	0.9	0.055	16	0.7	0.043
4	0.7	0.043	17	0.4	0.024
⋮	⋮	⋮	⋮	⋮	⋮
10	0.7	0.043	23	0.8	0.049
11	0.6	0.037	24	0.7	0.043
12	0.8	0.049	25	0.6	0.037
13	0.9	0.055	26	0.4	0.024

5.2 Obtained results

In the location problem, the best hub location is determined to minimize both the total transportation costs from factories to distribution centers and from DCs to customers. According to Table 3, point 13 named Kia kola is the optimal location with the lowest objective function.

After identifying the most appropriate hub location, the bi-objective inventory-routing model can be implemented in the case study. Meanwhile, the obtained pareto optimal points are computed based on the model IV and reported in Figure 3.

The planning horizon for the problem under study is 15 days. In this way, 15 periods with different routes need to be investigated, as presented in Table 4.

The amount of delivery and pickup products to/from customers is one of the main variables in the inventory control procedure. The demands are determined daily, and order quantity is announced to the factories. After that, the dairy products are stocked in the warehouse and subsequently distributed to customers through vehicle routings. When delivering a new product, the deteriorated products must be collected from the customer within the planning horizon. For example, for the fifth period, the amounts of products delivered to the customer as well as the collected spoiled products are shown in Table 5.

Table 3: The value of the objective function of the proposed hub location model

Candidates	Objective function	Candidates	Objective function
1	8,824,000	14	7,795,000
2	8,734,000	15	7,751,000
3	8,876,000	16	7,932,000
4	8,945,000	17	7,876,000
⋮	⋮	⋮	⋮
10	7,639,000	23	9,186,000
11	7,593,000	24	8,809,000
12	7,035,000	25	8,959,000
13	7,031,000	26	7,932,000

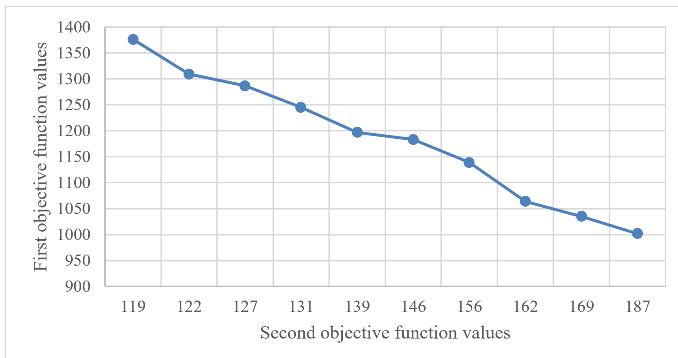

Figure 3: The obtained pareto optimal points of the bi-objective inventory-routing model

Table 4: Customer visiting sequences for each route in selected periods

Period (P)	Route	Customers Sequence
P1	Route 1	$13 \to 10 \to 11 \to 9 \to 8 \to 7 \to 6 \to 4 \to 2 \to 3 \to 1 \to 5$
	Route 2	$13 \to 10 \to 11 \to 9 \to 8 \to 7 \to 6 \to 4 \to 2 \to 3 \to 1 \to 5$
	Route 3	$13 \to 26 \to 21 \to 25 \to 24 \to 23 \to 22 \to 19 \to 20$
P2	Route 1	$13 \to 9 \to 10 \to 11 \to 8 \to 5 \to 1 \to 2 \to 4 \to 3 \to 6 \to 7$
	Route 2	$13 \to 12 \to 16 \to 15 \to 17 \to 18 \to 14$
	Route 3	$13 \to 19 \to 21 \to 26 \to 22 \to 25 \to 24 \to 23 \to 20$
⋮	⋮	⋮
P14	Route 1	$13 \to 11 \to 9 \to 8 \to 10 \to 5 \to 3 \to 1 \to 4 \to 2 \to 6 \to 7$
	Route 2	$13 \to 14 \to 17 \to 18 \to 15 \to 16 \to 12$
	Route 3	$13 \to 20 \to 21 \to 24 \to 25 \to 22 \to 23 \to 26 \to 19$
P15	Route 1	$13 \to 11 \to 10 \to 8 \to 9 \to 5 \to 1 \to 2 \to 4 \to 3 \to 6 \to 7$
	Route 2	$13 \to 12 \to 16 \to 15 \to 17 \to 18 \to 14$
	Route 3	$13 \to 20 \to 19 \to 23 \to 24 \to 25 \to 22 \to 26 \to 21$

Table 5: The quantity of products distributed and collected during the fifth period

i	ν_{ir}^5			n_{ir}^5		
	yogurt	...	Drinks	yogurt	...	Drinks
1	6	...	6	1	...	0
2	46	...	1	1	...	0
3	17	...	1	0	...	0
4	43	...	5	0	...	0
5	1	...	0	0	...	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮
24	0	...	0	0	...	0
25	11	...	0	1	...	0
26	18	...	3	0	...	0

According to the daily demands, the order quantity of the products in each period is determined and sent to the customers. Due to the perishability of dairy products, some products may spoil during storage. In this case, the product may be out of stock and customer demand may not be met. Additionally, due to the limited number of vehicles and prioritization of customers, some of the products may not be delivered to customers. We need to meet customers' demands as much as possible while minimizing inventory levels. In this respect, table 6 shows the amount of stock, warehouse-to-factory order quantities, and backorders.

Table 6: The order quantity, inventory level, and back order in the fourth to sixth periods

Products	g_r^4	h_r^4	b_r^4	g_r^5	h_r^5	b_r^5	g_r^6	h_r^6	b_r^6
Yogurts	654	0	11	886	45	0	723	52	23
Milks	665	0	2	751	33	0	748	48	11
Buttermilks	438	15	0	576	0	2	614	9	0
Cheeses	539	0	8	691	0	4	686	18	0
Sauces	248	0	0	289	0	5	479	22	0
Drinks	225	9	0	325	41	8	489	16	7

6 Discussion

In this section, some parameters have been selected to evaluate the outcomes of the proposed model with the existing procedures of the company. In other words, the results of the proposed approach are compared with existing strategies in terms of costs, delivery time, back order, and inventory level. Meanwhile, the obtained results are compared to current practice and Gitinavard et al. [18]' study to indicate the reliability of the proposed approach. In the ensuing lines, these comparisons are given in detail. Finally, managerial implications are provided to clearly represent the practical application of the proposed approach.

6.1 The comparison of the proposed hub location model with current practice

In the current situation, the closest potential place to the factory is customer number 4. However, the proposed hub location methodology offers customer number 13. During the planning horizon, the transportation costs from factories to customers are 8945000 IRR and 703100 IRR in the former and later points, respectively. The results indicate that costs are reduced by up to 22% and Gitinavard et al. [18]' study could improve the current practice by 21.39%.

6.2 The comparison of proposed inventory-routing model with real practice

6.2.1 Delivery time

According to experts' views, three vehicles are considered to serve 26 customers. Each vehicle must deliver products to customers and then return to depot only once a day. Considering the uncertainty demands and time window, the

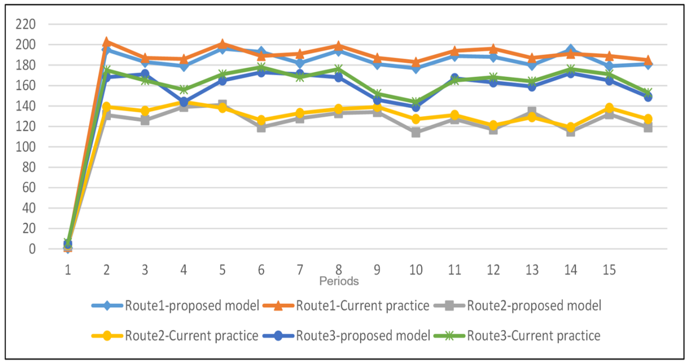

Figure 4: The comparison of delivery time between the proposed inventory-routing model and current practice

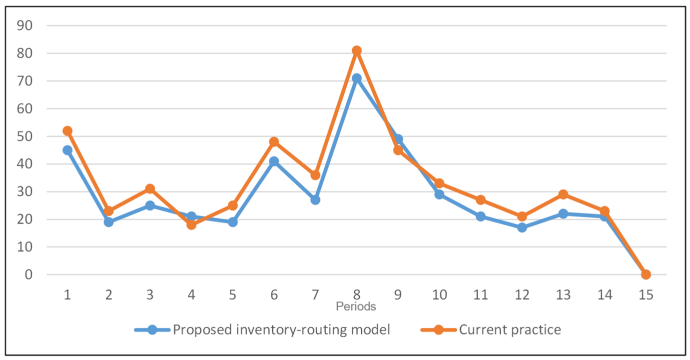

Figure 5: The backorder level in the proposed inventory-routing model and current practice

optimal path is determined in each period. Therefore, three routes are analyzed and the results illustrate that delivery time in the proposed model is shorter than the current situation in most periods, as depicted in Figure 4.

6.2.2 Backorder level

The warehouse orders are sent to the factory, which may result in backorder. This may occur in two cases: First, to meet the needs of important customers and considering the limited capacity of vehicles, the demands of other customers may not be answered. Second, due to the spoilage rate of products, some products may deteriorate in the warehouse and decrease the amount of stock. The backorder must be answered by the end of horizon planning. Efficiency can be improved by up to 24% using the proposed model compared to current practice. In this manner, Gitinavard et al. [18]' study could improve the current practice by 13.21%. In both the proposed model and the current model, the backorder in different periods is shown in Figure 5.

6.2.3 Perishable products

As mentioned in the previous sections, when delivering products to customers, spoiled products should also be picked up due to the limited capacity of vehicles. In comparison to real practice, the proposed model as well as Gitinavard et al. [18]' study improves the number of deteriorating items by 16.48%. The summary results are shown in Figure 6.

6.2.4 The inventory levels

Due to the perishable nature of dairy products, companies have to keep the balance between out-of-stock and waste production. High inventory level increases holding costs. Hence, the manufacturer is trying to minimize the inventory level and backorder simultaneously. Compared with real practice, the proposed model as well as Gitinavard et al. [18]' study can lead to a 12.86% improvement in the distribution centers. The mentioned results are presented in Figure 7.

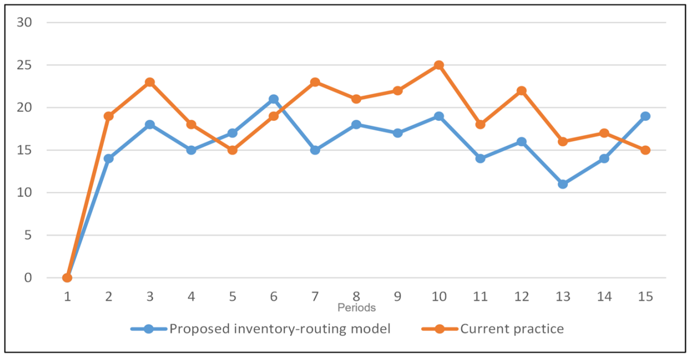

Figure 6: The perishable products in the proposed inventory-routing model and current practice

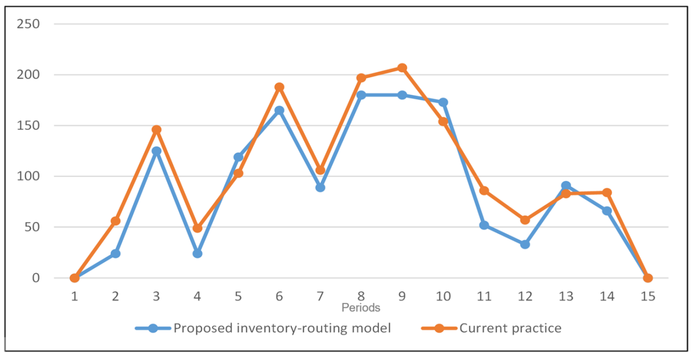

Figure 7: The inventory level in the proposed inventory-routing model and current practice

6.3 Managerial implications

The findings of this study offer several valuable managerial insights for designing an efficient supply chain for perishable products, summarized as follows:

- To remain competitive and thrive in the dairy products market, it is essential to focus on several key factors, including pricing, delivery time, time windows, distribution efficiency, service quality, and deviations from customer preferences.
- The proposed method evaluates the significance of customers by analyzing their order history and distance from the warehouse. This allows companies to improve customer satisfaction by reducing service deviations for high-priority customers.
- The proposed model emphasizes the timely delivery of goods to customers. However, adapting it to other industries may require specific modifications, such as incorporating multiple hub warehouses or allowing for flexible delivery time windows.
- By integrating both routing and warehousing operations, this approach enables companies to develop efficient warehousing strategies based on incoming orders.
- An integrated framework for hub location and vehicle routing, which manages the order-to-factory process and product distribution, effectively minimizes costs associated with inventory holding, backorders, and delivery.
- A comparison between the augmented -constraint method and the proposed approach revealed a set of Pareto-optimal solutions. It is recommended that decision-makers select final solutions from within this efficient frontier.
- Given the perishable nature of the products, manufacturers must consider spoilage rates between production and delivery, as these impact shortage and backorder costs. Furthermore, incorporating seasonal expiration rates into the model can enhance its applicability to real-world scenarios.

- The implementation of the integrated routing and warehousing model resulted in a reduction of total distribution time. Additionally, stockouts, inventory levels, and the gathering of expired products were reduced by 13.21%, 12.86%, and 16.48%, respectively.
- The case study indicated that choosing an optimal warehouse location can significantly reduce distribution costs by up to 21.39%.
- The strategic selection of warehouses is crucial for minimizing travel time and costs within the supply chains of perishable goods.
- Considering a medium-size problem is a limitation of this study that solving large-size problem may require heuristic algorithm.

7 Concluding remarks and future directions

Cold chain logistics of perishable products can play a key role by focusing on time window delivery limitations in the competitive market environment. Therefore, this approach has to optimize supply chain elements' locations, inventory levels and delivery routes. In this study, a bi-phase robust possibilistic mixed integer non-linear programming model is tailored to solve the hub location-routing problem for the cold chain of perishable products. In this sake, the proposed bi-phase robust possibilistic model solved the problem with objectives of minimizing the total costs and reducing the backorder rate for important customers. To achieve this, the proposed multi-objective model was converted into a single objective model by implementing the augmented -constraint method with Pareto optimal points analysis. The robust possibilistic approach is then applied to the proposed bi-phase hub location-routing model to cope with imprecise demand. The verification of the proposed bi-phase robust possibilistic mixed integer non-linear programming model is checked by defining a real-case study about cold chain logistics of perishable products. The proposed model can reduce 22% of total costs according to variable optimizations. Finally, a comparative analysis is provided to compare the obtained results from the proposed approach against the current practice. Meanwhile, the proposed approach improved the backorder level by 24%, the number of deteriorating items decreased by 16.48%, and the inventory levels enhanced by 12.86%. For future directions, a robust possibilistic programming approach can be developed based on hesitant fuzzy membership functions to cover the ambiguity uncertainty by considering some membership values. In addition, the proposed model is implemented in a real-case with medium size that is a limitation of this study and solving the large-size problem by considering the heuristic algorithm is valuable. Moreover, an agent-based modeling approach and heuristic algorithms can be manipulated to design a hub location-routing system for cold chain logistics of perishable products under soft computing approaches [1, 23].

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