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Sustainable p-hub Median Modeling for Perishable items in presence of Fuzzy Setting

Saeed Zameni[1]. Seyed Esmaeil Najafi[1*]. Seyed Mohammad Haji Molana[1]. Seyed Mojtaba Sajadi[2]

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*Corresponding Author, e-najafi@srbiau.ac.ir

1- Department of Industrial Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
2- Operations and Information Management Department, Aston Business School, Aston University, Birmingham, B4, 7ET, UK

Abstract
This study introduces a sustainable p-hub median model for perishable items considering fuzzy transport times. It is the first to address time uncertainty in a sustainable hub location for perishable products. The multi-objective mixed-integer nonlinear programming model optimizes transportation costs, product quality, CO2 emissions, and social impacts such as job creation. The model is validated using GAMS software on small to medium datasets, demonstrating that incorporating social responsibility alters network design and enhances overall objectives. This research offers a novel approach to sustainable supply chain management by balancing economic, social goals, and environmental, and provides a practical framework for real-world implementation.

Keywords - Food supply chain; Fuzzy multi-objective nonlinear programming; P-hub median problem; perishability; Sustainable supply chain

INTRODUCTION

For proper food storage, items should be protected from factors that cause spoilage. The development and application of research models for food supply chain operations have garnered significant attention from researchers [1]-[2]. Fresh produce, like fruits, is highly perishable with a limited shelf life. Also, unlike other products, the quality of this particular type of product is constantly reduced during downstream activities in the supply chain [3]-[5]. For this reason, the planning process of food supply chain networks is complex in terms of the type of products used in these networks. Accounting for product perishability, especially in the food supply chain, is a primary concern for distributors. This directly impacts the responsiveness of the network. Because perishability is time sensitive and it decreases over time. Given this fact, choosing an optimal distribution network is an essential factor for the logistics system manager. Therefore, the food supply chain focuses more on product quality and should pay attention to minimizing shipping time or maximizing product quality at delivery time. While the growth of global distribution companies has generated employment opportunities, it has also led to increased greenhouse gas emissions, particularly CO2 [6]-[8].

Green hub location problem has been studied by Golestani et.al [9] with two objectives: first, maximizing the quality of the delivered product, and the second, minimizing the emission of air pollutants and the total system costs. In the given supply chain, several types of perishable products can be distributed simultaneously, as mentioned [10]. Each non-hub node must be connected to at least one hub and there must be a valid path between each two hubs. This ensures that there is a path between both pairs of origin and destination [11]. Many Dairy Companies use hub networks to transfer perishable dairy products from origin to destination [12]. Recently, sustainable supply chain management has garnered significant research interest [13]-[15]. Beyond the costs associated with transporting and equipping members of the supply chain, the sustainability features of the network are also of paramount importance. In sustainable supply chain management, attention to social issues and environmental protection are important points of sustainability, which include controlling the occurrence of social harms and controlling carbon emissions around the world. Kumar et al. reviewed a complete literature in sustainable food supply chain. They provided valuable information about how each research, itself, contributes to the sustainability of food supply chains [16]. To design a sustainable distribution network, social and environmental impacts must be considered as a separate decision criterion [17]. Aghaei Afshar et al. [18] identified the mismanagement of the cold food supply chain that may jeopardize food safety and reduce quality. They considered suppliers and the cost of quality distribution services and developed a two-objective model of cost and quality of the entire supply chain and solved it in a parametric way. Thus, rather than solely focusing on transportation costs and network responsiveness, as seen in many traditional supply chain challenges, it's critical to consider diverse objective functions to optimize network sustainability. In this paper, we introduce a novel multi-objective hub location problem for a sustainable food supply chain, emphasizing the cost-saving aspects of the hub network structure.

Unlike traditional supply chain problems, our approach prioritizes different objective functions, ensuring a balance between transportation costs, product quality, and sustainability. In hub location problems, to manage operational costs, loads from nodes assigned to a specific hub are first aggregated at that hub before being dispatched to the destination-associated hub. Under this type of transportation arrangement, instead of sending directly from manufacturers to customer areas, products are aggregated and distributed in hubs. Given that loads are often sent to a hub after aggregation of all allocated nodes, it is very important to check the timing of the output vehicles. The goals of this issue are minimizing the total cost of transporting and equipping the hubs, maximizing the freshness and quality of the products at the moment of delivery, and locating the two issues of job creation in areas with high unemployment and reduced carbon emissions. This helps to avoid locating hubs in highly polluted areas and to minimize vehicle carbon emissions. Hub location problems have significant applications in many areas of research, especially facility location problems.

Fahmy et al. [19] formulated a NP-hard facility location-allocation problem for perishable products using a mixed integer linear programming model, proposing hybrid algorithms (BPSO and SA) to minimize spoilage, transportation, processing, and hub establishment costs. Wang et al. [20] developed a comprehensive model that addresses multiple objective functions, including emissions, delivery time, costs, and the alignment of supply and demand over time. Their study introduced a novel approach to integrate and standardize these objectives into a single weighted objective. Agustina and Piplani [21] proposed a proper mixed linear programming for the problem of vehicle scheduling and routing in a transit warehouse. They considered the issue of time windows to ensure that food products are delivered on time. Etemadnia et al. [22] studied a logistics network for vegetables and fruits that achieved optimal location of wholesale hubs on a national scale. A new multi-objective multi-period hub location model that tries to decrease costs and emissions and on the other hand, enhances job opportunities by focusing on managing the operational capacity of facilities throughout the planning horizon is proposed by Khaleghi and Eydi [23]. In this research demand flow is assumed time-dependent as a fuzzy parameter in order to make the model more real.

Pourghader et al. [24] presented a multi-objective hub location model for perishable tourism products. In this problem they consider the perishable factor of the products, some places are located for perished products. So, the combination of a hub-spoke network and a supply chain is assessed. Then the distributors are considered as a set of hubs. Elyasi and Teymuri [25] considered an agri-food supply chain as a complex system consisting of three subsystems, namely economic, environmental and social. Then, they utilized, for the first time, a meta-methodology called the Critical Systems Practice to cope the supply chain sustainability. Jaigirdar et al. [26] presented a multi-objective supply chain model for perishable products that considers cold storage, lead time, total cost, and customer satisfaction. The model uses a MILP formulation, a CPLEX solver, and various methods to find the optimal trade-offs among the objectives. The model is applied to a case study of fresh produce distribution in India. Yin et al. [27] introduced a novel customer satisfaction objective within a robust multi-objective hub location problem framework. This objective is characterized by two key factors: satisfaction with transportation quality and satisfaction with transportation time.

Razmi and Rahmaniniyay [28] have identified the issue of the middle hub as appropriate for the network at which delivery is important. A multi-objective mathematical model of linear programming is proposed. This model reduces costs and latency at the same time by maximizing customer satisfaction. Due to the fact that the cost and capacity of establishing hubs are different, their selection was based on the needs of the network. In this research, demand, establishment CO_2 emission and fuzzy parameter transport time have been considered, which has not been done before. In this study, unlike other activities, instead of reducing service time, it focuses on reducing latency. Heydari et al. [29] have designed a mathematical model for a sustainable supply chain network, considering the number of hubs, the types of products, the quantities, and the quality levels that should be produced by each manufacturer to satisfy the demands of various distribution centers. So, a multi-objective problem introduced considering transportation costs, hub construction costs, and production costs as an economic issue, carbon emissions from cars as an environmental issue, employment creation, and regional development as a social responsibility to achieve sustainability. Zijoodi et al. [32] reviewed literature on sustainable supply chain management, focusing on process improvement, waste reduction, efficiency, supplier relationships, hub location optimization, and strategies for managing uncertainty. Mohammadi et al. [35] developed a multi-objective model for optimizing sustainable perishable food supply chains, focusing on pricing, cycle length, facility locations, and delivery modes to maximize profit and minimize costs. Eydi et al. [34] presented a bi-objective mathematical programming model for designing a capacitated hierarchical hub center network for perishable products. They used multiple allocation to minimize transportation costs and maximum travel time, ensuring network responsiveness and equity among customers. Table 1 inspects the literature in terms of 6 main factors:

TABLE 1
LITERATURE SUMMARY

RESEARCH	SOCIAL RESPONSE	FUZZY TRAVEL TIME	PERISHABLE	P-HUB MODEL	INTERHUB DISCOUNT RATE	DISTANCE
RAHMANNIYAY & RAZMI (2020)		✓		✓		✓
HEIDARI ET AL. (2021)	✓			✓	✓	✓
GOLESTANI ET AL. (2021)			✓	✓	✓	✓
KHALEGHI & EYDI (2022)	✓			✓	✓	✓
ELYASI & TEYMURI (2023)	✓		✓			
YIN ET AL. (2023)				✓	✓	✓
JOUZDANI & GOVINDAN (2021)	✓		✓			✓
MOHAMMADI, BARZINPOUR, & TEIMOURY (2023)	✓		✓			✓
FAHMY ET AL. (2023)			✓	✓		✓
EYDI, VAZIRI, & KHALEGHI (2024)	✓		✓	✓	✓	✓
THIS WORK	✓	✓	✓	✓	✓	✓

The logistics of food supply chains, particularly for perishable items, pose unique challenges due to the time-sensitive nature of the products involved. The preservation of product quality from the point of origin to the consumer is paramount, as spoilage can result in significant financial loss and wasted resources. Traditional supply chain models often overlook the impact of transportation time on perishability, leading to suboptimal network designs that fail to maximize product freshness. In recent years, there has been a growing interest in integrating sustainability into supply chain management, reflecting a broader societal emphasis on reducing environmental impact and enhancing social responsibility. This research contributes to the evolving field of sustainable supply chain management by introducing a novel multi-objective hub location problem specifically tailored for perishable goods.

Our model uniquely incorporates the uncertainty of transport times through the use of fuzzy logic, addressing the real-world challenge of unpredictable delivery durations that can critically affect product quality. This is the first study to integrate fuzzy transport time uncertainty into a sustainable hub location model for perishable items, thereby offering a more realistic and applicable approach to modern supply chain challenges. Furthermore, unlike traditional models that focus primarily on cost, this research optimizes for a balance between economic efficiency, environmental impact, and social equity, ensuring a more holistic approach to sustainable supply chain management. By optimizing transportation costs, minimizing CO_2 emissions, and promoting job creation in economically disadvantaged areas, this research provides a holistic framework that aligns with contemporary sustainability goals. The model's validation through empirical data and its application using GAMS software demonstrate its practical relevance and potential for real-world implementation.

PROBLEM DESCRIPTION AND MODELING

This paper introduces a single-allocation p-hub median problem within a fuzzy environment. The goals of both maximization and minimization are weighted, leading to the optimal solution for node location and allocation. The model in this paper innovatively combines economic, environmental, and social factors with fuzzy logic to address transport time uncertainty in sustainable hub locations for perishable goods. While it uses established methods, their unique application and integration offer a fresh and valuable contribution to the field. The sustainability of the hub network can be analyzed from multiple perspectives. Among these, three factors - social, environmental, and economic - stand out as pivotal in determining a hub network's sustainability. In this context, we've delineated three distinct objectives encompassing economic, environmental, and social goals. Unemployment, a significant social concern, not only disrupts societal equilibrium but also precipitates numerous crises. Beyond its immediate implications, unemployment fosters various social and economic challenges. Addressing unemployment can alleviate many of these intertwined issues.

Consequently, our first objective function revolves around the strategic location of hubs to bolster employment in areas grappling with high unemployment rates. In the contemporary era, a significant chunk of environmental concerns stem from transportation and traffic, both of which contribute substantially to daily pollutant emissions. These pollutants encompass carbon monoxide (CO), nitrogen oxide (NO_2), carbon dioxide (CO_2), among others. Beyond transportation, industrial operations further exacerbate environmental degradation through their emissions. The study aims to develop a sustainable p-hub median model for perishable items by incorporating fuzzy transport times. This model seeks to optimize the location and allocation of hubs in a food supply chain to achieve the following outcomes:

1. Minimization of Transportation Costs: By efficiently locating hubs and aggregating demands, the model aims to reduce overall transportation costs.
2. Maximization of Product Quality: Ensuring timely delivery to maintain the freshness of perishable products.
3. Reduction of CO_2 Emissions: Incorporating environmental considerations to minimize carbon emissions associated with transportation.
4. Promotion of Social Responsibility: Enhancing job creation in areas with high unemployment rates.

Given this backdrop, an optimal network design would minimize pollutant emissions. Each facility and transportation mode contributes a specific quantum of pollution. Notably, much of the extant literature on supply chain environmental considerations zeroes in on carbon dioxide (CO_2) emissions, which we've adopted as our focal point. Thus, our second objective function aims to curtail CO_2 emissions by judiciously locating hubs, thereby reducing inter-node transport and averting excessive traffic and activities in hub-centric cities. Our final objective function is crafted to pinpoint optimal hub locations, factoring in both transportation costs and the cumulative distance between nodes allocated to a particular hub. Given the inherent uncertainties and occasional inconsistencies in real-world scenarios, problem parameters often lack precision. Yet, many studies adopt a deterministic stance on these parameters. Experts and decision-makers typically rely on historical data to estimate these parameters, but the reliability of such estimates remains contentious. Hence, it's often more pragmatic for decision-makers to adopt an indeterminate approach or lean on linguistic expression parameters. In this study, we've embraced a fuzzy approach to uncertainty, primarily due to ambiguities surrounding parameter distribution, information accuracy, and parameter antecedents. To infuse a touch of realism, we've treated the time parameter between two nodes as fuzzy numbers. The core assumptions underpinning our novel model are:

- The hub network achieves completion by interconnecting all hub pairs.
- The designated number of hubs is predetermined, amounting to p.
- Non-hub nodes are restricted from direct communication.
- The problem adheres to a p-hub median archetype, with each non-hub node exclusively allocated to a single hub.
- Inter-node travel time adopts a triangular fuzzy number format (triangular distribution A=0.2).
- Node locations are unequivocally defined, with every node possessing the potential to metamorphose into a hub.
- Each node's requirements are aggregated from source nodes and dispatched from source hubs to the destination hub. The destination hub, in turn, caters to its nodes, encompassing the destination node.

This section subsequently delves into the mathematical model, which is predicated on the aforementioned assumptions.

TABLE 2
INDICES, PARAMETERS AND VARIABLES

Indices	
X, Y	Set of nodes {x,y= 1, 2, . . . , j}
M, N	Nodes located as Hub {m, n = 1, 2, . . . , p}
Parameters	
p	Number of Hubs
f_{xy}	Flow between x,y
d_{xy}	Distance between x,y
E_x	Carbon dioxide level in the air of node x
S_x	Unemployment rate of node x
$\tilde{t}_{xy}$	Travel time between x,y
Eb_m	maximum time to collect loads from different nodes
β	Economic discount factor (inter-hub connections)
θ	Environment discount factor (inter-hub connections)
Pt	Perishable time
Variables	
z_{xn}	$\begin{cases} 1 & \text{if node x allocate to hub n} \\ 0 & \text{otherwise} \end{cases}$

According to the above explanations, the model is formulated as follows:

$$Min\ Z(1) = \sum_{m}(1-S_m).z_{mm}$$

$$Min\ Z(2) = \sum_{m} E_m.z_{mm} + \sum_{x}\sum_{y}\sum_{m}\sum_{n}\theta.f_{xy}(z_{xm}.z_{yn}.d_{mn}) \tag{1}$$

$$Max\ Z(3) = \sum_{x}\sum_{m}\sum_{y} z_{xm}.(f_{xy}+f_{yx}).d_{xm} + \sum_{x}\sum_{y}\sum_{m}\sum_{n}\beta.f_{xy}.z_{xm}.z_{yn}.d_{mn}$$

s.t.

$$\sum_{m} z_{xm} = 1 \qquad \forall x \tag{2}$$

$$\sum_{m} z_{mm} = p \tag{3}$$

$$z_{xm} \le z_{mm} \qquad \forall x,m \tag{4}$$

$$\max\{(\tilde{t}_{xm}.z_{xm})\} = Eb(m) \qquad \forall m \tag{5}$$

$$z_{ik}.z_{jm}.(Eb_m + \tilde{t}_{mn} + \tilde{t}_{yn}) \le Pt \qquad \forall x,y,m,n \tag{6}$$

$$z_{xy} \in \{0,1\} \qquad \forall x,y,m,n \tag{7}$$

Constraint (2) specifies the allocation of individual non-hub nodes to hubs. Constraint (3) guarantees the selection of the number of p hubs in the network. The allocation of nodes to their hubs is determined by constraint (4). Constraint (5) determines the maximum time to collect loads from different nodes of hub (m). Constraint (6) guarantees the delivery of goods in less time than the time of corruption. Constraint (7) indicates that the allocation is a binary variable. Fuzzy models are mathematical tools used to represent uncertainty and imprecise information. Different methods exist for defining fuzzy models based on how fuzzy numbers are ranked. This study uses the method by Jimenez et al. [35], which involves ranking fuzzy numbers to determine justification for the answer vector and the concept of an acceptable optimal solution. This method is suitable for this study because it considers the travel time parameter as a triangular fuzzy number in the constraints and preserves the linearity of the problem for accurate solution. Jimenez et al.'s approach is particularly suitable for this study due to its simplicity, robustness, and ability to preserve the linearity of the model, which is crucial for efficient optimization in complex problems like the sustainable hub location. Its effectiveness in handling triangular fuzzy numbers and its proven track record in various applications make it a reliable choice for capturing real-world uncertainties in transport times, ensuring that the model remains both practical and computationally feasible. The auxiliary equations 5 and 6 corresponding to the proposed model are as follows. Assuming that the fuzzy parameters are triangular fuzzy numbers.

$$\max\{((1-\alpha).\frac{t_{xm}^1+t_{xm}^2}{2}+(\alpha).\frac{t_{xm}^2+t_{xm}^3}{2}).z_{xm})\} = Eb(m) \qquad \forall m$$

$$\begin{aligned} & z_{xm}.z_{yn}.(Eb_m + ((1-\alpha).\frac{t_{mn}^1+t_{mn}^2}{2}+(\alpha).\frac{t_{mn}^2+t_{mn}^3}{2}) \\ & +((1-\alpha).\frac{t_{yn}^1+t_{yn}^2}{2}+(\alpha).\frac{t_{yn}^2+t_{yn}^3}{2})) \le Pt \end{aligned} \qquad \forall x,y,m,n$$

To solve this three-objective model, methods such as Multi Objective Decision Making (MODM) are needed. The additive method with equal weights was chosen for its simplicity and clarity, ensuring balanced consideration of economic, environmental, and social objectives. It reduces model complexity, making the multi-objective optimization more feasible and easier to interpret in real-world applications. The objective function will be as follows:

$$Min\ Z = w_1.(Z_1) + w_2.(Z_2) - w_3.(Z_3)$$

In this problem, the method of weighting the objective functions is used equally ($w_1 = w_2 = w_3 = \frac{1}{3}$).

RESULT AND DISCUSSION

The proposed nonlinear model will be solved and validated. For this purpose, a small-scale problem has been solved by GAMS23.5 software. The AP dataset, which contains 200 nodes data, has been used, but because the problem is NP-Hard and will take time to resolve, only part of the information is sufficient, so that only the first 8 nodes for a review of the proposed mathematical model is used:

TABLE 3
NODE COORDINATES (I,J)

nodes	i	j
1	24497	0
2	24497	10
3	7205	1448
4	24497	1448
5	7205	4344
6	57640	4344
7	24497	5792
8	7205	7240

If we draw the nodes on a plane, the map will be similar to Figure 1.

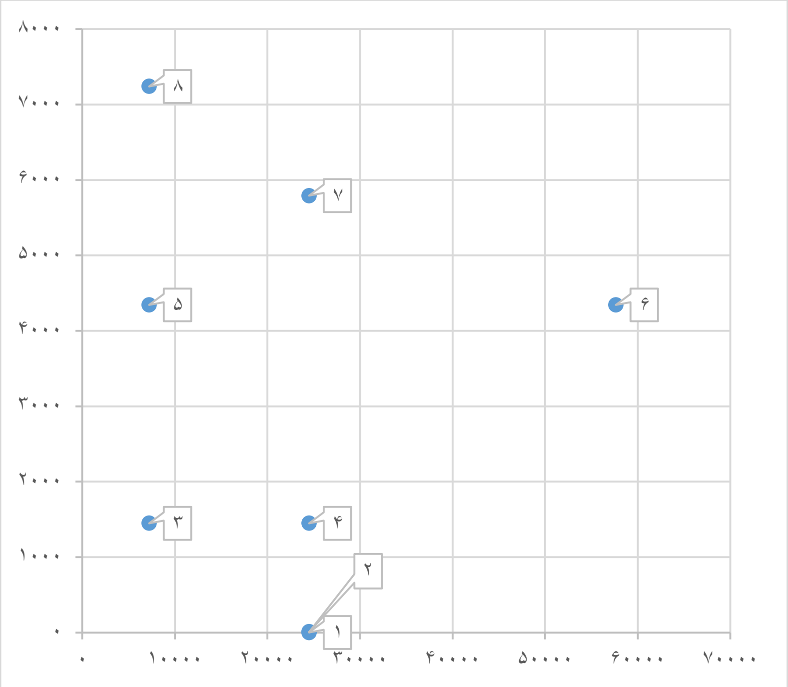

FIGURE 1
MAP OF AUSTRALIAN POST DATASET NODES IN COORDINATE SYSTEM (8 FIRST NODES)

TABLE 4
THE DISTANCE BETWEEN THE NODES

d(x,y)	1	2	3	4	5	6	7	8
1	0	10	17352	1448	17829	33426	5792	18746.4
2	10	0	17351	1438	17826	33425	5782	18742.6
3	17352	17351	0	17292	2896	50518	17829	5792
4	1448	1438	17292	0	17532	33269	4344	18236.2
5	17829	17826	2896	17532	0	50435	17352	2896
6	33426	33425	50518	33269	50435	0	33174	50518.0
7	5792	5782	17829	4344	17352	33174	0	17352.5
8	18746	18742	5792	18236	2896	50518	17352	0

TABLE 5
THE FLOW OF MOVEMENT BETWEEN NODES

f(x,y)	1	2	3	4	5	6	7	8
1	0	0.01	0.1852	0.3947	0.01	0.0953	0.5150	0.32455
2	0.01	0	0.01	0.01	0.01	0.01	0.01	0.01
3	0.1936	0.01	0	0.1976	0.01	0.0477	0.2579	0.16253
4	0.1927	0.01	0.0923	0	0.01	0.0475	0.2567	0.16176
5	0.0126	0.01	0.01	0.0128	0	0.01	0.0168	0.01059
6	0.0718	0.01	0.0344	0.0733	0.01	0	0.0957	0.06031
7	0.3025	0.01	0.14492	0.3088	0.01	0.0746	0	0.25394
8	0.1146	0.01	0.0549	0.1170	0.01	0.0282	0.1526	0

Travel time will also be as follows, assuming the distance is proportional:

TABLE 6
TRAVEL TIME (HOUR) BETWEEN NODES (DIRECT)

t(x,y)	1	2	3	4	5	6	7	8
1	0	0.01	173.5	14.4	178.2	334.2	57.9	187.4
2	0.01	0	173.5	14.3	178.2	334.2	57.8	187.4
3	17352.5	17351.6	0	172.9	28.9	505.1	178.2	57.9
4	14.4	14.3	172.9	0	175.3	332.6	43.4	182.3
5	178.2	178.2	28.9	175.3	0	504.3	173.5	28.9
6	334.2	334.2	505.1	332.6	504.3	0	331.7	505.1
7	57.9	57.8	178.2	43.4	173.5	331.7	0	173.5
8	187.4	187.4	57.9	182.3	28.9	505.1	173.5	0

Estimated environmental consequences of the hub location at the node m equal to E(m) and unemployment rate at the node m is assumed S(m) as follows:

TABLE 7
NODES FEATURES

node	E(m)	S(m) (percent)
1	10	5
2	100	10
3	40	20
4	100	30
5	10	10
6	10	15
7	5	20
8	50	10

Assuming location for two hubs (p=2), discount factors (β=0.2, θ=0.7) and maximum of 30 days (720 hours) to prevent the corruption of perishable goods, the network is optimized as follows. The optimal value is 28221.843. Now, the demand of perishable goods in the sustainable hub network has been optimally met in conditions close to the real world, and it can be benefited by implementing it in the real world.

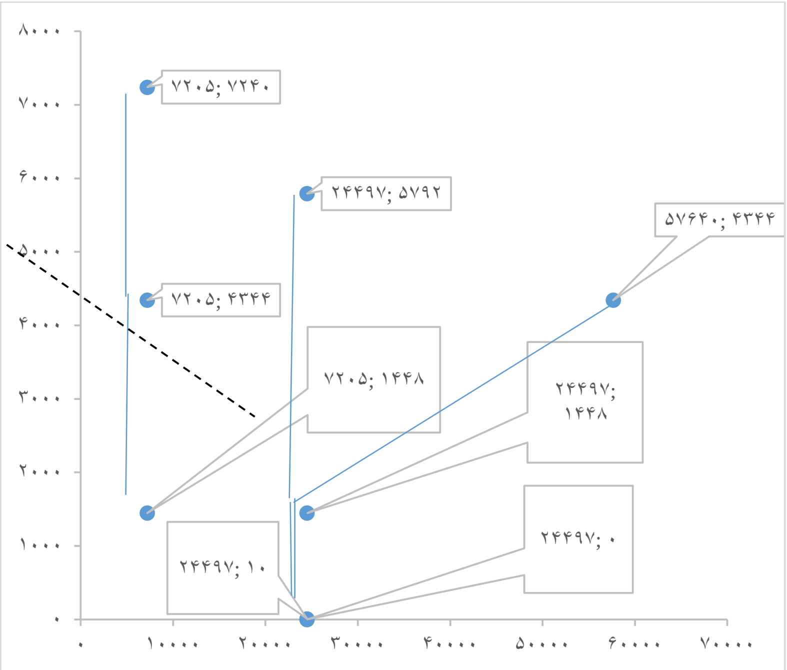

FIGURE 2
AUSTRALIA POST (8 NODES) OPTIMUM SOLUTION

According to Figure 2, nodes 4 and 5 were selected as hubs and the allocation of nodes was done optimally (Table 8).

TABLE 8
NODES ALLOCATION

node	Allocated hub
1	4
2	4
3	5
4	4
5	5
6	4
7	4
8	5

The time limits for each node for the origin hubs are as shown in Table 9.

TABLE 9
PROPERTIES OF EACH NODE MAXIMUM ORDER TIME (FUZZY TRIANGULAR) UNTIL DELIVERY IN THE OPTIMAL NETWORK PROBLEM 1

node	with source hub number 5	with source hub number 4
1	(151.76, 189.7, 227.64)	(11.52, 14.4, 17.28)
2	(151.68, 189.6, 227.52)	(11.44, 14.3, 17.16)
3	(23.12, 28.9, 34.68)	(163.36, 204.2, 245.04)
4	(140.24, 175.3, 210.36)	0
5	0	(140.24, 175.3, 210.36)
6	(406.32, 507.9, 609.48)	(266.08, 332.6, 399.12)
7	(174.96, 218.7, 262.44)	(34.72, 43.4, 52.08)
8	(23.12, 28.9, 34.68)	(163.36, 204.2, 245.04)

According to Table 9, the maximum delivery time for demand to the nodes in this example is associated with the nodes that are last in the delivery routes. Specifically, nodes 4 and 6 have times of 106.328 and 121.936 hours, respectively, both of which are well below the 720-hour threshold. The maximum times on the routes for each hub are 66.81 and 38.218 hours. The prioritization of objective functions can vary based on societal values, especially when considering environmental, economic, and social dimensions. As illustrated in the target weighting table (Table 10) and the subsequent sensitivity analysis, the importance assigned to each objective can significantly influence the results. A comparison of the outcomes from problems 2 and 3 reveals a notable shift: when the social responsibility factor is excluded (as in problem 2), the location of the hubs is altered, leading to an increase in the objective function value. This observation underscores the pivotal role of social considerations in shaping the hub network.

TABLE 10
OBJECTIVE FUNCTIONS WEIGHT

	Problem 1	Problem 2	Problem 3
$\boldsymbol{w_1}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{5}$
$\boldsymbol{w_2}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{5}$
$\boldsymbol{w_3}$	$\frac{1}{3}$	0	$\frac{2}{5}$

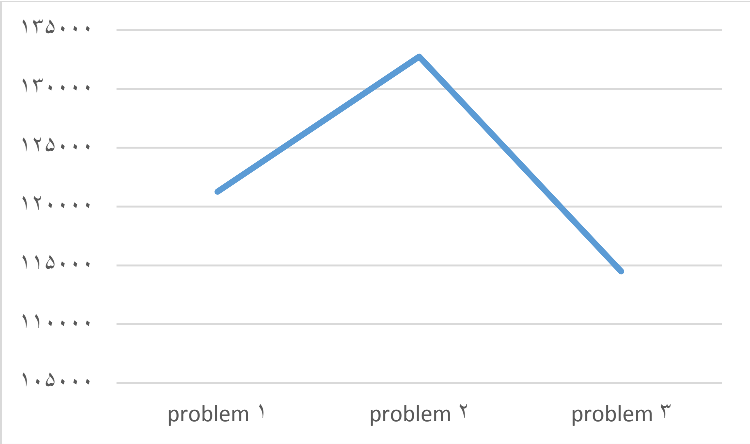

FIGURE 3
RESULT OF PROBLEMS

The outcomes derived from problems 1, 2, and 3, as presented in Table 11, highlight the profound impact of different goal prioritizations on the overall network design. It's evident that varying conditions and objective weightings can lead to diverse network configurations.

TABLE 11
RESULT OF PROBLEMS

Problem	Objective function value	Selected nodes as hub
1	121254	4, 5
2	132755	4, 5
3	114478	3, 4

In terms of computational performance, using GAMS23.5, the problem-solving durations were 6 seconds for an eight-node problem, 37 seconds for a fourteen-node problem, and 7236 seconds for a twenty-node problem. The exponential increase in computation time with problem size is a testament to the NP-Hard nature of the problem.

CONCLUSION

In this study, we introduce a novel p-hub median model tailored for sustainable food supply chains. Within this model, each hub node is characterized by its cost, environmental, and social impacts. The model designates certain nodes as hubs, allocates blades to these hub nodes, and assigns vehicles to serve customers. This multifaceted problem, with its three distinct objective functions, yields varied solutions based on specific scenarios. To enhance the model's realism, we've incorporated the time parameter as fuzzy numbers. To validate the model's precision and conduct a sensitivity analysis, we've applied it to smaller datasets. For future endeavors, the integration of supply chain contracts could be explored. Moreover, adhering to regulations aimed at curbing air pollution or streamlining the supply chain could further refine the proposed model. Given that solving nonlinear problems using the DICOPT solver can produce imprecise results, we advocate for the linearization of the problem to ensure accuracy. Additionally, the development of heuristic algorithms might offer a viable solution for large-scale challenges. Our study introduced a novel p-hub median model tailored for sustainable food supply chains, emphasizing the balance between economic, environmental, and social dimensions. The results of our research provide valuable insights into the optimization of hub locations and allocations. Key findings include:

- Efficient delivery Times: Nodes 4 and 6, which are last in the delivery routes, have maximum delivery times of 106.328 and 121.936 hours, respectively. These times are significantly below the 720-hour threshold, showcasing the efficiency of the proposed model.
- Impact of objective Prioritization: The sensitivity analysis, based on the target weighting table, revealed that the prioritization of objectives can significantly influence hub locations and the overall objective function value. Notably, sidelining the social responsibility factor led to a shift in hub locations.

- Comparative Analysis: The outcomes from problems 1, 2, and 3 highlighted the profound impact of different goal prioritizations on the overall network design.
- Computational Performance: The model showcased efficiency with problem-solving durations of 6 seconds for an eight-node problem, 37 seconds for a fourteen-node problem, and 7236 seconds for a twenty-node problem. However, the exponential increase in computation time with problem size indicates the NP-Hard nature of the problem.
- Practical Relevance: The model's validation using GAMS software demonstrates its applicability and potential for real-world implementation, providing a robust framework for sustainable supply chain management.

In conclusion, our research underscores the importance of a holistic approach to sustainable food supply chain management. The balance between economic, environmental, and social considerations is pivotal, and our model provides a robust framework for achieving this balance. Here are some recommendations for future research:

- Advanced Computational Techniques: Given the NP-Hard nature of the problem, there's a need to explore more efficient algorithms or heuristic methods that can handle larger datasets without a significant increase in computational time.
- Incorporation of Real-world Data: Future studies could integrate real-world data from various food supply chains to validate the model's applicability and robustness in diverse scenarios.
- Dynamic Models: Consider developing dynamic models that can adapt to changing conditions in real-time, such as fluctuating demand, supply disruptions, or changing transportation conditions.
- Develop models that adapt to real-time changes in supply chain conditions, like fluctuating demand or transportation disruptions, using IoT and big data analytics.

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