Journal of Intelligent Management Decision
https://www.acadlore.com/journals/JIMD

A Mathematical Model for Optimizing Postal Supply Chain Networks and Facility Location

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Received: 12-01-2024 **Revised:** 01-20-2025 **Accepted:** 02-08-2025

Citation: H. Fazlollahtabar, "A mathematical model for optimizing postal supply chain networks and facility location," *J. Intell Manag. Decis.*, vol. 4, no. 1, pp. 44–52, 2025. https://doi.org/10.56578/jimd040103.

Abstract: The strategic positioning of distribution, sales, and service facilities plays a critical role in ensuring the efficiency, reliability, and cost-effectiveness of supply chains. In particular, the location of such facilities within the transshipment network significantly influences both operational costs and consumer satisfaction by affecting delivery times and service quality. This study introduces a mixed-integer linear programming (MILP) model designed to optimize the layout of a postal supply chain network. The model aims to minimize the key cost components, including transportation, facility location, and holding costs, within a four-echelon supply chain consisting of suppliers, warehouses, retailers, and recipients. Parcels are initially collected by suppliers and delivered to regional warehouses, which then allocate them to selected retail locations. The selection of optimal retail locations is based on a cost minimization criterion, after which parcels are transported to the final delivery points—post offices situated in various cities. A distinctive feature of the proposed model is the assumption that demand at the recipient level is determined at the supplier level, thereby facilitating more centralized demand management and reducing uncertainties in the planning process. The model incorporates several constraints, such as flow balance, capacity limitations, and retailer selection. The optimization problem is solved using LINGO 16 software, and a comprehensive analysis is conducted to identify the optimal configuration of retailer locations and parcel flow distribution. A numerical example is provided to demonstrate the practical application of the model, and sensitivity analysis is performed to assess the impact of key parameters—such as retailer capacity and initial inventory levels—on the overall cost. The results indicate that increasing retailer capacity leads to a reduction in total supply chain costs, highlighting the benefits of economies of scale and parcel consolidation. However, an increase in the initial quantity of parcels results in higher costs due to elevated transportation and holding expenses. These findings offer valuable insights for decision-makers seeking to optimize postal supply chains, balancing the need for cost efficiency with the provision of high-quality service.

Keywords: Postal supply chain; Facility location; Mixed-integer linear programming (MILP); Cost optimization; Retailer selection; Sensitivity analysis

1 Introduction

The supply chain is a complex system that requires a holistic approach to ensure its effective functioning. Its primary objective is to deliver finished products—whether materials, services, or both—to customers. Key components of the supply chain include warehouses and the connections between various points in the transfer network. The efficiency of the supply network relies heavily on the management and coordination of logistics facilities, which perform essential functions such as storage, buffering, picking, and distribution. Continuous optimization of these activities is crucial, focusing on resource efficiency and work organization. Among the factors influencing the reliability and performance of the supply chain, the strategic location of infrastructure points plays a pivotal role [1–3].

To enhance operational performance in postal delivery chains, the International Post Corporation (IPC) offers technological and collaborative solutions. These solutions aim to help member postal operators achieve shared objectives and meet commercial demands [4]. They address various aspects of the mail delivery process and improved operational equipment [5]. In response to evolving post-network and transport industry dynamics, as well as growing market demands, the IPC has initiated efforts to foster reliability and sustainability. By bringing together postal operators, the initiative focuses on improving service quality, interoperability, and cost-effective operations [6].

One notable initiative is the Post Network, designed to optimize transport capacity utilization, enhance ease of use, ensure better protection of postal items, and minimize operating costs [7]. Its stacking capabilities maximize volume exploitation, particularly in truck cargo space and load capacity utilization [8]. The Post Network serves as an overnight road transport system for priority letters, offering an alternative to reduced transport capacity. It has significantly improved delivery quality and enabled transport synergies for participating postal organizations [9].

Cargo distribution to customers is a critical aspect of the supply chain, ensuring the flow of materials to end users. Urban areas present unique challenges for distribution, requiring careful planning and control of the physical movement of finished products. Economic factors and infrastructure availability must also be considered in this process [10, 11]. While transportation of goods is vital for economic and social development in urban areas, it can also lead to traffic congestion and safety concerns. However, well-organized transport systems can stimulate growth [12, 13]. Therefore, developing methods to positively influence the distribution process—such as reducing transport work in cities—is essential. This is particularly important for the supply chain as a whole and its individual components, emphasizing the significance of strategic storage and handling facility locations [14, 15].

Apologies for the earlier misunderstanding. Upon reviewing the available literature, it appears that comprehensive studies specifically focusing on "post office supply chain management" are limited. However, several related works address aspects of supply chain management within postal services. Below is a literature review comprising 13 pertinent studies, each referenced in bracketed numbering style.

Ittmann [16] evaluates the mail delivery performance of the South African Post Office (SAPO) from both international and local perspectives, emphasizing logistics and supply chain management aspects. The study highlights challenges in SAPO's service reliability and underscores the need for significant efforts to enhance its supply chain operations. The U.S. Government Accountability Office (GAO) report discusses the progress of the United States Postal Service (USPS) in implementing supply chain management initiatives. The report identifies successes and challenges, providing insights into the application of commercial best practices within postal services [17]. A study by Teymouri et al. [18] explores the application of revenue management in the supply chain of postal services. The authors develop a conceptual model aimed at optimizing capacity utilization and maximizing revenue, addressing capacity limitations in induction processes. Vinodh et al. [19] investigate the impact of lean service practices, workplace environment, and social practices on the operational performance of India's postal service industry. The study finds that lean practices significantly enhance productivity and flexibility, contributing to improved operational performance. Crew and Brennan [20] edit a comprehensive volume discussing the future of the postal sector amidst digital transformation. The book covers various aspects, including supply chain management, and provides insights into adapting to a digital environment. Crew and Kleindorfer [21] compile research on the progress toward liberalization in the postal and delivery sector. The work examines the implications of liberalization on supply chain management within postal services. Crew and Kleindorfer [22] delve into the dynamics of competition and regulation in the postal and delivery sector. The book discusses how these factors influence supply chain strategies and operations. Dablanc and Rakotonarivo [23] analyze the impacts of logistics sprawl on energy efficiency in goods movement, using Paris as a case study. Their findings are relevant to postal services' supply chain management, particularly in urban settings. Dragendorf et al. [24] discuss strategies for postal networks to succeed in the age of e-commerce. The report emphasizes the importance of adapting supply chain management practices to meet the demands of e-commerce. Chopra and Meindl [25] provide a comprehensive overview of supply chain management strategies, planning, and operations. While not exclusively focused on postal services, the principles discussed are applicable to postal supply chain management. Färe et al. [26] examine inefficiencies in postal services, providing insights into areas where supply chain management can be improved. The study offers a framework for understanding and addressing inefficiencies. Cohen [27] discusses the challenges faced by postal services in the digital age, including supply chain management issues. The article highlights the need for postal services to adapt their supply chain strategies to remain relevant. The Universal Postal Union (UPU) provides metrics for assessing postal development performance, which include aspects of supply chain management. These metrics offer a benchmark for evaluating and improving postal supply chain operations [28].

This paper addresses the organization of cargo distribution in urban areas, focusing on the final segment of the supply chain, which utilizes cargo consolidation centers and transshipment retailer locations. The proposed distribution organization concept involves selecting transshipment retailer locations based on a cost index. The distribution plan aims to identify the optimal retailer location while minimizing associated costs. A four-echelon supply chain network—comprising supplier, warehouse, retailer, and receiver—is developed for the post network. The model seeks to minimize total costs by optimizing retailer locations and parcel transshipment quantities between facilities. Example calculations are provided to demonstrate the effectiveness of the proposed method.

The paper is structured as follows: Section 2 introduces the problem statement, Section 3 presents numerical experiments to validate the model, and Section 4 concludes with key findings and implications.

2 Problem Statement and Formulations

This paper presents a supply chain network for the postal system, specifically designed to optimize retailer locations. The proposed network consists of four echelons: supplier, warehouse, retailer, and recipient. The flow of parcels between these facilities is as follows: suppliers collect parcels and send them to warehouses, which then distribute them to potential retailer locations. Based on cost considerations, the optimal retailer location is selected. Finally, parcels are delivered to recipients, which are post offices in various cities. The total cost of the problem includes transportation costs, fixed costs for opening retailers, and warehouse holding costs. This section introduces an optimization model aimed at minimizing transportation costs, with the output being the optimal retailer location and the quantity of parcels shipped between facilities.

The model is based on the following assumptions:

• The problem operates under certainty.
• The initial quantities are predetermined.
• The locations of retailers are known.
• The locations of recipients are known.

The notations are given in Table 1:

Table 1. List of notations

Sets and Parameters	
J	Counter for parcels (1. . . j. . . J)
S	Counter for suppliers (1. . . s. . . S)
W	Counter for warehouses (1. . . w. . . W)
K	Counter for retailers (1. . . k. . . K)
Z	Counter for recipients (1. . . z. . . Z)
E_{sw}	Distance between supplier and warehouse
E_{wk}	Distance between warehouse and retailer
E_{kz}	Distance between retailer and recipient
L_{swj}	Transportation cost of parcel j per km between supplier and warehouse
G_{kwj}	Transportation cost of parcel j per km between warehouse and retailer
R_{kzj}	Transportation cost of parcel j per km between retailer and recipient
H_w	Holding cost of warehouse
B_k	Fixed-cost for retailer k
Cap_k	Capacity of retailer
Cap_w	Capacity of warehouse
λ	The coefficient of quantity of parcels to be sent to each recipients
Decision variables	
Y_k	1, if the retailers which is located in site k is utilized to send parcels, 0, otherwise
P_{swj}	Quantity of parcel j 'sent by supplier to warehouse
V_{wkj}	Quantity of parcel j 'sent by warehouse to retailers
T_{kj}	Quantity of parcel j 'sent by distribution to recipients

Mathematical model:

The proposed model can be written as follows:

$$\text{Min } Z = COF + TC + HC \tag{1}$$

$$COF = \sum_{k} B_k Y_k \tag{2}$$

$$TC = \sum_{w}\sum_{k}\sum_{j} (G_{wkj} K_{wk} V_{wkj}) + \sum_{s}\sum_{w}\sum_{j} (L_{swj} E_{sw} P_{swj}) + \sum_{k}\sum_{z}\sum_{j} (R_{kzj} E_k T_{kzj}) \tag{3}$$

$$HC = \sum_{w}\sum_{j}\sum_{s} p_{swj} h_{wj} \tag{4}$$

$$\sum_j \sum_w v_{wjk} \leq cap_k \cdot y_k \qquad \forall k \tag{5}$$

$$\sum_k v_{wjk} = \sum_s p_{swj} \qquad \forall w, j \tag{6}$$

$$\sum_s \sum_j p_{swj} \leq cap_w \qquad \forall w \tag{7}$$

$$\sum_s p_{swj} = Q_{0(j)} \qquad \forall w, j \tag{8}$$

$$\sum_k T_{kj} = \sum_w \lambda_{jz} V_{wkj} \qquad \forall j, k, z \tag{9}$$

$$Y_k \in \{0, 1\} \qquad \forall k \tag{10}$$

$$P_{swj}, V_{wkj}, T_{kzj} \geq 0 \qquad \forall j, s, w, k, z \tag{11}$$

Eq. (1) defines the objective function, which minimizes the total cost in the Closed-Loop Supply Chain (CLSC) network. Eq. (2) accounts for facility-related costs, while Eq. (3) incorporates holding costs, including associated expenses. Constraint set (4) specifies the capacity limitations of retailers. Constraint set (5) ensures that the quantity of parcels sent from the warehouse to retailers equals the quantity received by the warehouse from suppliers. Constraint set (7) outlines the capacity constraints of the warehouse. Eq. (8) defines the input quantity to the warehouse. Constraint set (9) determines the number of parcels sent from retailers to each recipient. Finally, constraint sets (10) and (11) define the binary and non-negative nature of the decision variables, respectively.

3 Results

The numerical implementation of the supply chain network optimization model involves translating the theoretical mathematical formulation into a practical problem that can be solved effectively. This process consists of several stages, including data preparation, model formulation, solver execution, and results analysis. The primary objective is to determine the optimal retailer locations and parcel flows that minimize the total cost while adhering to all constraints. The first step in the numerical implementation is the preparation of input data. This involves defining the parameters and variables necessary for the model. These parameters include the starting points of the supply chain, where parcels are initially collected; the intermediate facilities, where parcels are stored before being distributed to retailers; and the candidate locations for opening new retailer facilities. Additionally, the recipient locations—post offices in various cities—are identified as the final delivery points. The cost components essential to the model are also specified. These include the cost of transporting parcels between facilities, which is randomly generated on a per-parcel basis; the cost of opening a retailer location, generated randomly per retailer; and the cost of storing parcels in warehouses, generated per parcel. Furthermore, the demand at each recipient location (i.e., the number of parcels required at each post office) is established. Constraints such as the maximum number of parcels that can be shipped or stored at each facility are also included in the model to ensure operational feasibility. In this section, the necessary parameters for solving the problem are presented. The size of the problem is defined by the number of parcels (j), suppliers (s), warehouses (w), retailers (k), and recipients (z). The generated parameters required to solve the problem are provided in Table 2.

3.1 Analysis of Results

The numerical implementation demonstrates the effectiveness of the model in optimizing the supply chain network. Key insights include: optimal retailer locations are chosen to balance transportation and fixed costs; the parcel flows ensure that demand is met while minimizing costs; the total cost is dominated by transportation costs, highlighting the importance of efficient logistics. This section is dedicated to presenting and analyzing the results of solving the problem instances. The optimal solutions were obtained using LINGO 16 software, as shown in Table 3.

Table 2. Random generated values for parameters

Parameters	Values
B	U(5000,10000)
E_{sw}	U(30,40)
E_{wk}	U(30,40)
E_{kz}	U(30,40)
H_w	U(5,10)
R_{kzj}	U(8,12)
G_{wkz}	U(8,12)
L_{swj}	U(8,12)

Table 3. The outputs resulted from the implementation

Test Problem	$\lvert j\rvert \times \lvert s\rvert \times \lvert w\rvert \times \lvert k\rvert \times \lvert z\rvert$	Objective Function	CPU Time
1	$\lvert 2\rvert \times \lvert 1\rvert \times \lvert 3\rvert \times \lvert 4\rvert \times \lvert 2\rvert$	$2.3442 * 10^7$	0.6
2	$\lvert 3\rvert \times \lvert 1\rvert \times \lvert 4\rvert \times \lvert 3\rvert \times \lvert 3\rvert$	$1.0969 * 10^7$	2.5
3	$\lvert 4\rvert \times \lvert 1\rvert \times \lvert 5\rvert \times \lvert 4\rvert \times \lvert 3\rvert$	$0.1148660 * 10^7$	8
4	$\lvert 7\rvert \times \lvert 1\rvert \times \lvert 6\rvert \times \lvert 7\rvert \times \lvert 6\rvert$	$0.2148660*10^7$	35
5	$\lvert 8\rvert \times \lvert 1\rvert \times \lvert 7\rvert \times \lvert 9\rvert \times \lvert 8\rvert$	$0.1848660 * 10^7$	66

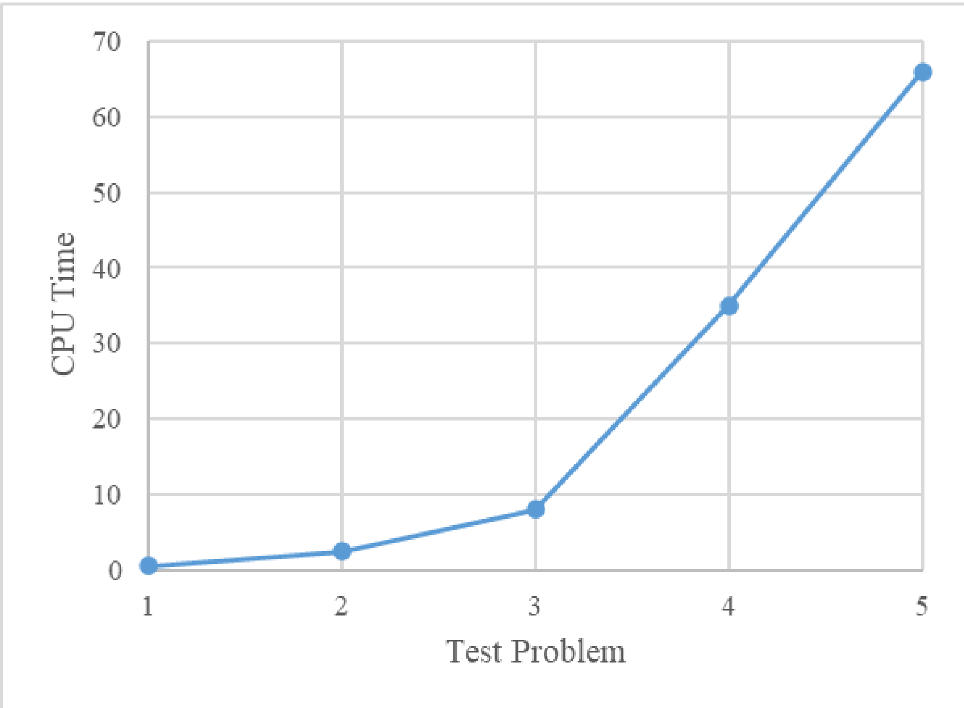

Figure 1. CPU time for different test problems

Figure 1 illustrates the CPU time required to solve the test problems. As depicted in the figure, the solution time increases nonlinearly with the size of the problem.

The numerical implementation successfully solves the supply chain network optimization problem, providing actionable insights for decision-makers. The model can be further refined by incorporating additional constraints or objectives, such as environmental impact or delivery time.

3.2 Sensitivity Analysis

This section examines the impact of retailer capacity and initial quantity on the objective function.

Sensitivity Analysis on Retailer Capacity: As shown in Figure 2, increasing the retailer's capacity leads to a decrease in the objective function value.

Sensitivity Analysis on Initial Quantity: As illustrated in Figure 3, increasing the initial quantity results in an increase in the objective function value.

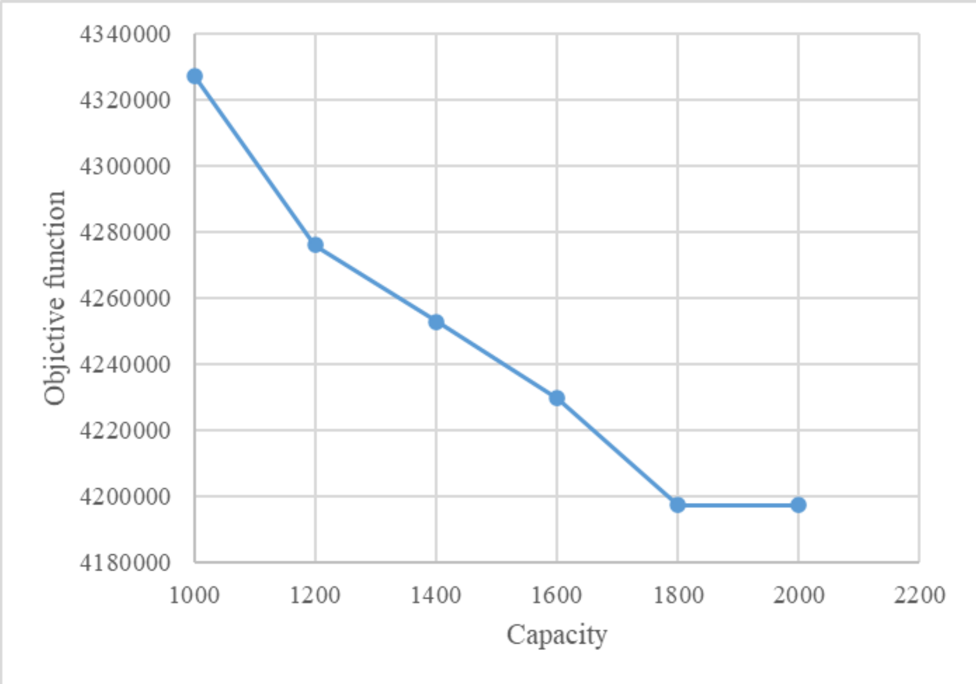

Figure 2. Objective function values variations for different amount of retailer capacity

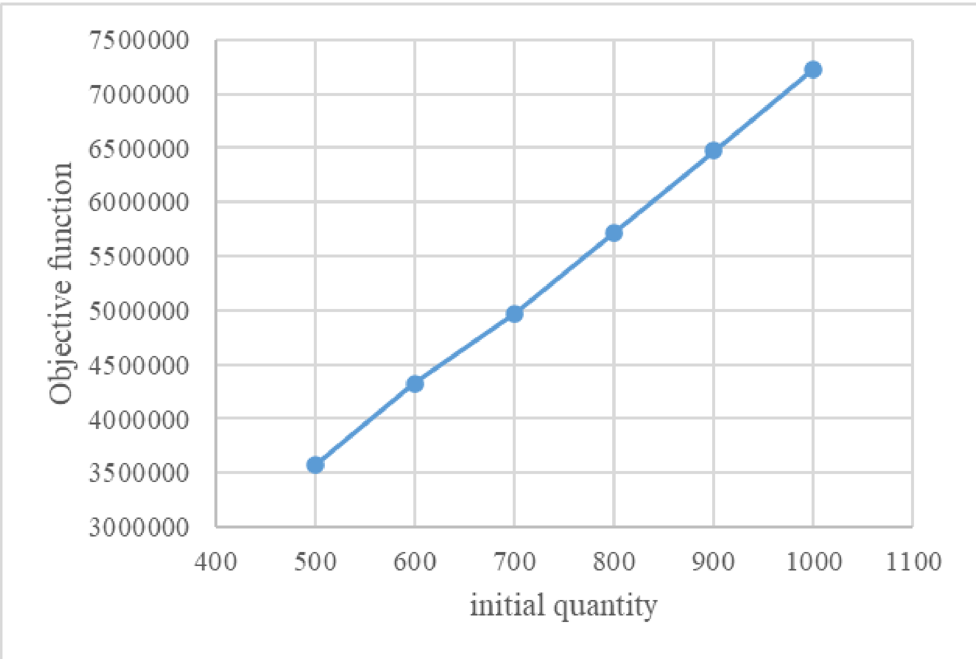

Figure 3. Sensitivity analysis for initial quantity variation impact on objective value

Sensitivity analysis is a critical tool for understanding how changes in key parameters affect the optimal solution of a model. In this case, the impact of retailer capacity and initial quantity were analyzed. The results show that the objective function value (total cost) decreases as retailer capacity increases. The objective function value increases as the initial quantity increases.

The decreasing trend in the objective function value with increasing retailer capacity can be explained as follows. As retailer capacity increases, the model can handle larger volumes of parcels at each retailer's location. This reduces the need to open additional retailers, thereby lowering fixed costs. Larger capacities also allow for more efficient parcel distribution, reducing transportation costs. Larger capacities enable economies of scale, where the cost per parcel decreases as the volume of parcels increases. Fewer retailers need to be opened, reducing the total fixed costs. With larger capacities, parcels can be consolidated and shipped more efficiently, reducing transportation costs.

Decision-makers should consider investing in larger retailer capacities to achieve cost savings. While larger capacities reduce costs, they may require higher upfront investments in infrastructure and technology. The optimal capacity depends on the balance between cost savings and investment requirements. Beyond a certain point, increasing capacity may yield diminishing returns, as other factors (e.g., transportation costs) become dominant. The benefits of larger capacities may be limited in scenarios with highly variable demand.

The increasing trend in the objective function value with increasing initial quantity can be explained as follows. As the initial quantity increases, the system starts with a larger inventory of parcels. This leads to higher holding costs, as more parcels need to be stored in warehouses. It may also increase transportation costs, as more parcels need to be distributed. A larger initial quantity increases the number of parcels stored in warehouses, leading to higher holding costs. More parcels need to be transported to meet demand, increasing transportation costs. Managing a larger initial quantity may require additional resources and planning, increasing operational costs.

Decision-makers should aim to optimize the initial quantity to balance holding costs and demand fulfillment. Accurate demand forecasting can help determine the optimal initial quantity to minimize costs. Implementing just-in-time strategies can reduce the need for large initial quantities, lowering costs. Reducing the initial quantity may increase the risk of stockouts if lead times are long. In scenarios with uncertain demand, maintaining a larger initial quantity may be necessary to ensure service levels.

The contrasting trends in the sensitivity analysis highlight the importance of balancing different factors in supply chain optimization. Increasing capacity generally leads to cost savings but requires careful consideration of investment requirements and demand variability. Reducing the initial quantity can lower costs but may increase the risk of stockouts and require accurate demand forecasting. The trade-offs between capacity vs. initial quantity show that decision-makers must balance the benefits of larger capacities with the costs of maintaining a larger initial quantity. For cost vs. service levels, optimizing costs may require trade-offs with service levels, such as delivery times and stockout risks.

The strategic recommendations include investing in larger capacities where feasible to achieve cost savings, implementing strategies to minimize the initial quantity, such as just-in-time inventory and demand forecasting, and considering the interactions between different factors (e.g., capacity, initial quantity, transportation costs) when making decisions.

The sensitivity analysis provides valuable insights into the impact of retailer capacity and initial quantity on the objective function value. The decreasing trend with increasing capacity highlights the benefits of economies of scale, while the increasing trend with increasing initial quantity underscores the importance of inventory optimization. Decision-makers should use these insights to make informed trade-offs and develop strategies that balance cost savings with operational efficiency and service levels.

4 Conclusions

The problem addressed in this paper is of significant importance due to its impact on the overall functioning of the supply network. The economic efficiency and reliability of the supply chain largely depend on its accurate organization. This paper proposes a mathematical model for designing a postal supply chain network aimed at minimizing transportation costs, facility location costs, and holding costs. The model serves effectively for optimizing the organization of distribution systems. The results demonstrate that the solution is of high quality and can be obtained in a short computational time. Based on the limitations of the model, several future research opportunities can be identified. These include conducting detailed research, performing in-depth analysis, and exploring modifications to the method. Potential extensions could involve differentiating costs, incorporating dynamic and random demand, introducing random travel times, or considering partial customer service or service failures with penalty charges. These avenues will be explored in future research endeavors.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

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