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Integrated Location-Routing-Inventory Optimization for Fair Vaccine Access: Addressing Perishable and Waste Complexity

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Abstract

Maintaining effective and fair vaccine distribution via temperature-controlled logistics is crucial for healthcare systems, especially when dealing with perishable products requiring strict climate control. Practical obstacles, such as fluctuating demand, spoilage monitoring needs, and expensive logistics, complicate operations. This research presents an optimization framework that combines depot selection, stock management, delivery routing, and expiration factors to address these issues. The solution seeks to reduce overall expenses while maintaining equitable access for all recipients, handling various vaccine formulations across multiple time frames. Parameter sensitivity tests evaluate how storage limits and demand variations impact performance. Findings confirm the model's ability to boost both economic performance and allocation equity, offering practical guidance for immunization logistics managers.

Keywords: Healthcare, Perishable, Facility location, Delivery routing, Inventory management, Supply chain.

1 | Introduction

The COVID-19 crisis revealed major flaws in medical supply chains, showing the need for a fast and fair vaccine delivery system, especially in uncertain situations. Solving this depends heavily on the Routing Problem (RP), which is crucial for efficiently transporting temperature-sensitive vaccines through cold supply chains that must keep strict temperature control to maintain effectiveness [1].

The fair allocation of vaccines is now a moral necessity. COVID-19 highlighted glaring gaps in availability between cities and countryside areas, as well as between wealthy and disadvantaged communities [2]. Shelf-

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life restrictions further complicate matters, setting tight deadlines for vaccine administration [3]. Such limitations demand careful coordination of delivery routes and timelines to avoid spoilage and loss.

Waste monitoring is another critical but neglected factor - tracking where and why vaccines get spoiled, expire, or are misused. Analyzing this data lets healthcare systems refine future distribution, enhance transparency, and minimize both financial and moral costs of preventable waste [4]. Effective vaccine distribution requires dynamic inventory systems. Unlike fixed approaches, these enable live adjustments to fluctuating supply and demand, crucial during health crises.

This research creates a system for vaccine chains, combining location selection, stock control, expiration monitoring, and route planning to balance costs, fairness, and eco-friendliness. The mathematical model accounts for practical limits like vaccine lifespan, storage space, delivery distances, and routing rules. Key innovations include: Tracking perishability during transport, connecting inventory levels across facilities with routing, and simultaneously improving financial and social outcomes.

2 | Literature Review and Research Gap

2.1 | Prior Research

Healthcare logistics research has progressed from basic routing and storage solutions to smart, adaptive systems as supply chains grow more complex. Duarte et al. [5] created a meningitis vaccine distribution framework balancing efficiency with ecological fairness. For COVID-19 vaccines in Europe, Khodaee et al. [6] developed a temperature-controlled model that cut expenses while improving availability. Separately, Nematollahi et al. [7] introduced a dual-level revenue model enhancing stock management and delivery quality while accounting for product expiration.

Building on these developments, Hashemi Amiri et al. [8] advanced the field with a resilient perishables' distribution framework that unified vendor choice, manufacturing schedules, and delivery routes while accounting for demand fluctuations. This approach found practical application in agricultural logistics, where Lin et al. [9] successfully implemented tiered service levels to optimize fresh produce distribution in local food networks, achieving measurable efficiency gains.

Lee et al. [10] created a dual-stage optimization framework combining Mixed-Integer Programming (MIP) with Column Generation (CG) to better manage oxygen distribution networks. Addressing vaccine delivery challenges, Ariningsih et al. [2] designed an adaptable distribution system using actual COVID-19 data from Indonesia. Meanwhile, Castillo's [11] team enhanced medical access in rural Spain by refining routing for mobile healthcare services. These approaches shared a common emphasis on adaptability and social value, demonstrating how logistical innovations can address real-world unpredictability while promoting equitable access.

The year 2025 witnessed growing technological integration in logistics solutions. Neroni et al. [12] pioneered an innovative framework for optimizing milk collection across multiple depots, complemented by six specialized heuristic approaches. This technological progression continued with Ikram et al. [13], whose breakthrough in 3D drone navigation algorithms substantially enhanced delivery performance, showcasing how cutting-edge innovations can transform traditional supply chain operations.

2.2 | Research Gaps and Contributions

A comprehensive review of existing studies reveals a notable research gap. No current work has holistically addressed the combined challenges of distribution routing, fair allocation, perishability constraints, spoilage monitoring, adaptive stock systems, and facility placement within a unified framework.

This study makes several significant advances:

I. Presenting an integrated optimization framework combining facility location, stock control, and perishability factors for vaccine distribution networks.

II. Accounting product expiration during transport by embedding shelf-life limitations into route planning.

III. Bridging inventory management with delivery logistics, enabling synchronized optimization of storage levels and transportation plans.

IV. Balancing cost efficiency with equitable access, ensuring fair vaccine allocation across all populations.

3 | Problem Definition and Mathematical Model

3.1 | Problem Statement

Maintaining vaccine integrity requires strict temperature control and rapid delivery, particularly in regions with limited resources. Creating an effective cold chain that guarantees fair and prompt distribution to medical centers poses both practical difficulties and moral responsibilities. Our research examines a hierarchical network connecting producers, hubs, storage units, and clinics.

Also, in this model, the distribution center can be considered as a hub. We address a distribution challenge that minimizes refrigeration expenses while satisfying needs and temperature requirements. The framework jointly optimizes depot placement, delivery paths, stock quantities, shelf-life restrictions, and range limits for cooled vehicles. A key feature involves factoring product expiry into logistics planning. Spoiled vaccines incur disposal fees, making precise timing essential. The system emphasizes equitable access, particularly for hard-to-reach areas, to ensure all facilities receive viable doses.

3.2 | Formulation

Vaccine distribution's urgent timeline demands cold chain optimization that simultaneously reduces transport expenses, environmental impact, and delivery times. *Table 1* details the model's core components and metrics.

Table 1. Notations.

Sets	
f	Storage warehouses in the system, where $f \in F$
s	Collection of centers distributing vaccines, where $s \in S$
w	Different types of vaccines available, where $w \in W$
b	Manufacturers producing vaccines, where $b \in B$
r	Healthcare facilities, where $r \in R$
g	Time intervals for planning, where $g \in G$
q	Vehicles with refrigeration, where $q \in Q$
l, u	Nodes in the system, where $l, u \in K \in (S \cup F)$
Parameters	
FQ_q	Base operational cost for refrigerated vehicle q
DN_{lu}	Travel distance from node l to node u
SC_{fw}^{max}	Vaccine type w storage limit at the warehouse f
SF_{sf}	Mileage between distribution site s and storage facility f
CQ_{qw}	Shipping cost per unit of vaccine type w using vehicle q
CS_s	Setup cost for vaccine hub s
VS_{sf}	Per-unit shipping expense between distribution points and storage facility f
BS_{bs}^{max}	Maximum permitted distance from producer b to any distribution point s
DN_{lu}^{max}	Allowable maximum distance between any two nodes l and u
SC_{sw}^{max}	Maximum vaccine w capacity at distribution center s
VB_{bs}	Shipping cost per vaccine unit from producer b to distribution hub s
BS_{bs}	Travel distance between production site b and distribution hub s
DV_{rwg}	Required amount of vaccine w at the health center r during time g
CV_{rwg}	Storage expense for vaccine w at facility r in period g
DF_{fr}	Mileage from cold storage f to medical facility r
VQ_{bwg}	Production output of vaccine w by manufacturer b in timeframe g
SH_w	Duration of the vaccine w remains effective.

Table 1. Continued.

FF_f	Setup cost for cold storage facility f
ED_w	Waste management cost for expired vaccine w
CC	Per-unit delivery expense from storage facilities to healthcare sites
NF	The maximum possible number of warehouses to choose from the available sites
Variables	
x_{frwg}	Amount of vaccine w sent from the storage facility f to the medical center r during time g
n_{sqg}	Auxiliary variable to prevent sub-tours in vehicle path planning
v_{fg}	1 if warehouse f operates in period g; 0, otherwise
e_{bsg}	1 if manufacturer b supplies distribution center s in period g; 0, otherwise
y_{rwg}	Stock level of vaccine w at the health facility r at the end of the period g
p_{sfwg}	Volume of vaccine w transported from distribution hub s to the warehouse f in period g
c_{swg}	Available vaccine w supply at distribution point s in cycle g
h_{sfg}	1 if warehouse f gets vaccines from hub s in period g; 0, otherwise
m_{qlg}	1 if transport q visits node l in period g; 0, otherwise
z_{rwg}	Expired doses of vaccine w at the medical center r during the interval g
o_{bfwg}	Vaccine w quantity delivered from producer b to storage site f in timeframe g
a_{sg}	1 if the distribution center is active in period g; 0, otherwise
d_{luqg}	1 if vehicle q travels from node l to u in period g; 0, otherwise

This paper proposes the following mathematical framework:

$$\min Z_1 = \sum_{g=1}^{G}\sum_{f=1}^{F} FF_f\, v_{fg} + \sum_{g=1}^{G}\sum_{f=1}^{F}\sum_{r=1}^{R}\sum_{w=1}^{W} CC\, x_{frwg}\, DF_{fr} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{w=1}^{W} CV_{rwg}\, y_{rwg} + \sum_{g=1}^{G}\sum_{r=1}^{R}\sum_{w=1}^{W} ED_w\, z_{rwg} + \sum_{g=1}^{G}\sum_{s=1}^{S} CS_s\, a_{sg} + \sum_{g=1}^{G}\sum_{b=1}^{B}\sum_{s=1}^{S}\sum_{w=1}^{W} VQ_{bwg}\, e_{bsg}\, BS_{bs}\, VB_{bs} + \sum_{g=1}^{G}\sum_{s=1}^{S}\sum_{f=1}^{F}\sum_{w=1}^{W} VS_{sf}\, p_{sfwg}\, SF_{sf} + \sum_{g=1}^{G}\sum_{l=1}^{K}\sum_{q=1}^{Q} FQ_q\, m_{qlg} + \sum_{g=1}^{G}\sum_{l=1}^{K}\sum_{u=1}^{K}\sum_{q=1}^{Q}\sum_{w=1}^{W} CQ_{qw}\, d_{luqg}\, DN_{lu}. \quad (1)$$

s.t.

$$\sum_{r=1}^{R} x_{frwg} = \sum_{b=1}^{B} o_{bfwg}\,, \forall f, w, g. \quad (2)$$

$$\sum_{f=1}^{F} x_{frwg} \geq DV_{rwg}\,, \forall r, w, g \geq g - SH_w. \quad (3)$$

$$\sum_{f=1}^{F} x_{frwg} = z_{rwg}\,, \forall r, w, g \geq SH_w. \quad (4)$$

$$y_{rwg-1} + \sum_{f=1}^{F} x_{frwg} - DV_{rwg} - z_{rwg} = y_{rwg}\,, \forall r, w, g \geq 2. \quad (5)$$

$$\sum_{r=1}^{R} x_{frwg} \leq SC_{fw}^{max}\, v_{fg}\,, \forall f, w, g. \quad (6)$$

$$\sum_{f=1}^{F} v_{fg} = NF\,, \forall g. \quad (7)$$

$$\sum_{s=1}^{S} e_{bsg} = 1\,, \forall b, g. \quad (8)$$

$$e_{bsg} \leq a_{sg}\,, \forall b, s, g. \quad (9)$$

$$\sum_{b=1}^{B} VQ_{bwg}\, e_{bsg} = c_{swg} \sum_{f=1}^{F} p_{sfwg}\,, \forall s, w, g. \quad (10)$$

$$\sum_{f=1}^{F} p_{sfwg} = c_{swg}\ , \forall s, w, g. \tag{11}$$

$$\sum_{f=1}^{F} p_{sfwg} \leq SC_{sw}^{max}\ , \forall s, w, g. \tag{12}$$

$$\sum_{s=1}^{S} p_{sfwg} \leq M \times v_{fg}\ , \forall f, w, g. \tag{13}$$

$$\sum_{w=1}^{W} p_{sfwg} \leq M \times h_{sfg}\ , \forall s, f, g. \tag{14}$$

$$\sum_{f=1}^{F} h_{sfg} = a_{sg}\ , \forall s, g. \tag{15}$$

$$\sum_{q=1}^{Q} m_{qsg} = \sum_{f=1}^{F} h_{sfg}\ , \forall s, g. \tag{16}$$

$$\sum_{q=1}^{Q} m_{qfg} \geq v_{fg}\ , \forall f, g. \tag{17}$$

$$m_{qfg} \leq v_{fg}\ , \forall f, q, g. \tag{18}$$

$$\sum_{f=1}^{F} m_{qfg} \leq 1\ \ , \forall q, g. \tag{19}$$

$$m_{qsg} - m_{qfg} \leq 1 - h_{sfg}\ , \forall s, f, q, g. \tag{20}$$

$$\sum_{l=1}^{K} d_{luqg} = m_{qug}\ \ , \forall u, q, g. \tag{21}$$

$$\sum_{u=1}^{K} d_{luqg} = m_{qlg}\ \ , \forall l, q, g. \tag{22}$$

$$n_{sqg} - Y_{s'qg} + L \times I_{ss'qg} \leq K - 1\ , \forall s, s', q, g. \tag{23}$$

$$DN_{lu} \leq DN_{lu}^{max}\ , \forall l, u. \tag{24}$$

$$v_{fg}\ \ , a_{sg}\ , e_{bsg}\ , h_{sfg}\ , d_{luqg}\ , m_{qlg} \in \{0, 1\}. \tag{25}$$

$$X_{frwg}\ \ , o_{bfwg}\ , p_{sfwg}\ , n_{sqg} \geq 0\ , \text{integer}. \tag{26}$$

Eq. (1) minimizes combined expenditures covering delivery, warehousing, waste handling, and infrastructure costs. *Eq. (2)* maintains shipment balance between distribution hubs and medical facilities. *Eq. (3)* requires fulfilling clinic needs within product viability periods. *Eq. (4)* classifies unused expired vaccines as wastage. *Eq. (5)* tracks medical facility stock levels, including previous reserves, incoming supplies, consumption, and perished units. *Eq. (6)* limits warehouse shipments by their refrigeration capacity. *Eq. (7)* specifies selecting precisely the Number of Facilities (NF) warehouses. *Eq. (8)* requires each producer to supply one hub per cycle. *Eq. (9)* restricts manufacturer assignments to active hubs. *Eq. (10)* balances production at each hub with its outgoing vaccines. *Eq. (11)* maintains shipment-supply balance at distribution centers. *Eq. (12)* caps deliveries by storage limits.

Eq. (13) restricts shipments to active warehouses. *Eq. (14)* mandates approved routes for center-to-warehouse transfers. *Eq. (15)* requires operational centers for vaccine distribution. *Eq. (16)* requires cooled transport for every functioning distribution hub. *Eq. (17)* mandates at least one vehicle per active storage facility. *Eq. (18)* limits vehicle assignments to operational warehouses. *Eq. (19)* restricts each vehicle to single-warehouse service per cycle. *Eq. (20)* enforces coordinated vehicle service between connected hubs and warehouses. *Eq.*

(21) requires active routes for all arriving vehicles. *Eq. (22)* mandates active paths for departing vehicles. *Eq. (23)* eliminates circular routes. *Eq. (24)* maintains travel within distance constraints. *Eqs. (25)* and *(26)* specify the model's variable types.

4 | Results and Model Validation

The model's effectiveness was assessed by solving various test cases. Equation-based solutions were derived for problems of different scales. *Table 2* displays sample optimal variables from one test case, with objective function values reaching 4,734,426. The results of this table reveal the model chooses one distribution center and one warehouse per period, showing a lean yet effective network meets demand. The manufacturer consistently supplies the same distribution center, suggesting stable sourcing driven by cost and proximity factors. Similarly, the warehouse receives shipments from a single distribution center, demonstrating consistent routing.

Shipment volumes from manufacturer to warehouse show minor period-to-period variations, with distribution center supplies also adjusting slightly. These small changes indicate the model responds to shifting demand and expiration timelines, preventing both shortages and overstocking. All routes stay within maximum distance parameters, satisfying both refrigeration requirements.

Table 2. Optimal results of the considered experimental problem.

a_{sg}		c_{swg}	
s1 . g1	1	s1 . w1 . g1	23
s1 . g2	1	s1 . w1 . g2	26
h_{sfg}		o_{bfwg}	
s1 . f1 . g1	1	b1 . f1 . w1 . g1	19
s1 . f1 . g2	1	b1 . f1 . w1 . g2	23
e_{bsg}		v_{fg}	
b1 . s1 . g1	1	f1 . g1	1
b1 . s1 . g2	1	f1 . g2	1

5 | Sensitivity Analysis

5.1 | Maximum Storage Capacity in Distribution Centers

Fig. 1 shows that total system cost decreases sharply as storage capacity grows from 800 to 2,000 doses, driven by reduced facility duplication and routing inefficiencies. Beyond 2,000 doses, costs stabilize as capacity constraints become inactive. Managers should target this threshold to optimize infrastructure investment while ensuring a reliable vaccine supply.

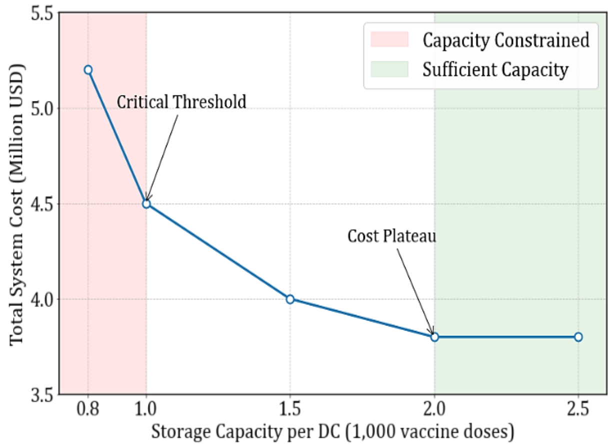

Fig. 1. Behavior of the objective function based on the parameter SC_{sw}^{max}.

5.2 | Demand for Types of Vaccines

Fig. 2 shows how vaccine demand variations affect total costs. Rising demand increases costs due to higher transportation, refrigeration, and inventory expenses. The steeper rise beyond 110% reflects added waste from shelf-life constraints and complex routing. This result highlights the need for demand-responsive logistics to balance access and costs during surges.

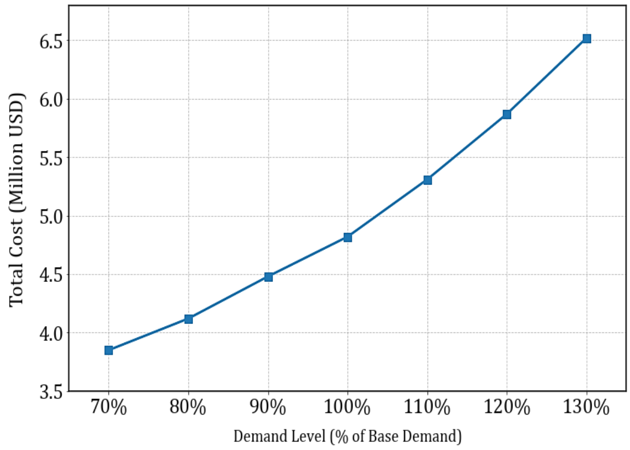

Fig. 2. Behavior of the objective function based on the parameter DV_{rwg}.

6 | Discussions and Practical Implications

Our solution stands out for its thoroughness and practical precision. The system integrates multiple critical elements: expiration timelines that change dynamically, inventory patterns affected by temperature, transportation limits, delivery timeframes, facility constraints, and fair distribution protocols. Together, these create a workable model for vaccine distribution that mirrors actual conditions. Such comprehensive detail allows for accurate scenario testing and practical deployment strategies during normal operations and outbreaks. The combination of scientific, operational, and community considerations offers health officials a valuable tool for making both effective and principled decisions.

For management, this model improves decision-making by streamlining coordination, predicting challenges, and refining distribution. It treats vaccine viability periods as planning factors, helping prevent wasteful shipments and minimize spoilage. The system builds on standard logistics metrics, transport limits, delivery times, stock levels, and local needs, ensuring practical adoption within current operations.

7 | Conclusion and Future Research

Delivering vaccines effectively goes beyond simple transportation - it directly impacts community health, fairness, and survival. This research addresses a critical healthcare logistics problem: distributing temperature-controlled immunizations equitably and efficiently, particularly given product expiration dates and remote populations. Our solution introduces a unified routing framework within a multi-echelon supply network. Breaking from conventional methods, this approach combines depot placement, stock management, perishability constraints, delivery routes, and accessibility concerns in a single optimization model.

Future research can explore several key areas. Dynamic or stochastic modeling may improve adaptability by accounting for demand fluctuations and operational disruptions. Machine learning could also refine demand predictions using past data and population trends, optimizing resource use and minimizing waste. Finally, integrating personalized equity measures could better align distribution with public health ethics.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability

All data generated or analyzed during this study are included in this published article. No additional data are available.

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