

Vaccine Cold Chain Distribution Optimization: A Literature-Based Operations Research Analysis

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Abstract

Vaccine distribution is a complex supply-chain problem because vaccines need to reach healthcare facilities in the required quantities while maintaining appropriate cold-chain conditions and keeping distribution costs under control. This project examines the use of Operations Research in vaccine cold-chain distribution through two published studies. Lin, Zhao and Lev (2020) study the choice between cold-chain and non-cold-chain transportation, while Sripada et al. (2023) develop a multi-tier decision-support framework for vaccine distribution. Drawing on these studies, a simplified capacitated network-flow model is developed for a distribution network linking a manufacturer, a state vaccine store, district stores and primary health centres. The model minimizes transportation cost, refrigerated vehicle-trip cost and shortage cost subject to supply, capacity, demand and vehicle-capacity constraints. In the base case, 4,600 doses are distributed without shortage at a total cost of ₹30,035. Sensitivity analysis is then used to examine changes in supply, demand and vehicle-related parameters. The results show how Operations Research can support practical, cost-conscious distribution decisions, while also highlighting the additional complexity created by uncertainty, inventory, expiry and cold-chain failure risk.

1. Introduction

Operations Research (OR) is a quantitative approach to decision-making that is useful when organizations have limited resources and several competing requirements. It uses mathematical models, optimization techniques and analytical methods to identify solutions that satisfy operational constraints while improving an objective such as cost, profit, service level or resource utilization.

Vaccine distribution is a particularly relevant real-world application of Operations Research. Vaccines are temperature-sensitive products, so inappropriate transportation or storage conditions can reduce their quality and effectiveness. At the same time, vaccine supply chains operate across several levels and face limits on transportation and storage capacity, changing demand and the need to avoid shortages. These characteristics make optimization useful for deciding how available vaccines should be allocated across a distribution network.

This project focuses on vaccine cold-chain distribution optimization and uses two research papers as its main literature foundation. Lin, Zhao and Lev (2020) examine the choice between cold-chain and non-cold-chain transportation and the economic implications of vaccine-quality risks. Sripada et al. (2023) develop a decision-support framework for optimizing vaccine distribution across a multi-tier cold-chain network. The present project draws on both studies to develop and analyze a simplified network optimization model using Excel Solver.

2. Real-Life Problem: Vaccine Cold Chain Distribution

A vaccine supply chain typically involves several stages between production and final administration. Vaccines may move from manufacturers to central or state-level stores, then to district facilities and finally to clinics or health centres. At each stage, managers have to decide how much vaccine should be moved, where it should go and how the available transportation capacity should be used.

The problem is more challenging because vaccines require controlled temperature conditions throughout the cold chain. A failure in the cold chain can result in loss of vaccine quality. Distribution decisions therefore need to balance cost and operational efficiency with the need for reliable vaccine delivery.

Operations Research is well suited to this problem because a distribution network can be represented using decision variables, an objective function and a set of constraints. An optimization model can then identify a cost-efficient allocation of vaccine doses while respecting supply, demand, capacity and transportation restrictions.

3. Literature Review

3.1 Lin, Zhao and Lev (2020)

Lin, Q., Zhao, Q., and Lev, B. (2020), in “Cold chain transportation decision in the vaccine supply chain,” examine a vaccine distributor’s decision over whether to use cold-chain (C) or non-cold-chain (NC) transportation. The study recognizes that transportation conditions can affect vaccine quality and incorporates the economic consequences of vaccine validity, transportation cost, equipment malfunction, temperature-recording malfunction, retailer trust and potential losses.

The study develops a decision framework in which cold-chain transportation becomes preferable when its additional cost is justified by lower expected losses and reduced quality-related risks. This study is useful for the present project because it establishes the operational and economic reasons for maintaining the cold chain.

3.2 Sripada et al. (2023)

Sripada, S., Jain, A., Ramamoorthy, P., and Ramamohan, V. (2023), in “A Decision Support Framework for Optimal Vaccine Distribution Across a Multi-tier Cold Chain Network,” develop an integer linear programming framework for vaccine distribution. The framework represents a multi-tier network involving manufacturers, vaccine stores and healthcare facilities.

The model considers decisions involving inventory, vaccine quantities transported, vehicle requirements, shortages, facility selection and healthcare personnel. Its objective is to minimize several categories of cost, including transportation, inventory holding, shortage, clinical service and labour-related costs. This study provides the main conceptual basis for the simplified network model developed in this project.

3.3 Comparison of the Two Studies

Aspect	Lin et al. (2020)	Sripada et al. (2023)
Main focus	Cold-chain vs. non-cold-chain transportation	Optimal vaccine distribution across a multi-tier network
Key concern	Vaccine quality and transportation risk	Cost-efficient network allocation
Approach	Transportation-mode decision framework	Integer linear programming
Important factors	Cold-chain cost, failures, trust, losses	Flow, inventory, vehicles, shortages, facilities, labour
Relevance here	Provides cold-chain risk context	Provides main network optimization foundation

3.4 Solution Methodology in the Selected Studies

Lin et al. (2020) use an analytical decision framework to examine whether a vaccine distributor should choose cold-chain or non-cold-chain transportation. Their analysis compares the additional cost of cold-chain transportation with expected losses and quality-related risks, while also examining factors such as equipment failure, temperature-recording failure, retailer trust and inspection policies.

Sripada et al. (2023) formulate vaccine distribution as an integer linear programming problem across a multi-tier cold-chain network. Their framework considers transportation quantities, inventory, vehicles, shortages, facility decisions and healthcare personnel. The study also extends the formulation to uncertainty and evaluates it through computational experiments and a case application.

The two studies therefore provide complementary foundations for this project. Lin et al. provide the cold-chain quality and risk perspective, while Sripada et al. provide the main network-optimization structure. The model developed here is intentionally simpler and is solved in Microsoft Excel Solver using the Simplex LP method with integer restrictions on vehicle-trip variables.

4. Mathematical Model

4.1 Network Structure

The simplified network used in the analysis is: Manufacturer → State Vaccine Store → District 1 / District 2 → PHC 1–4.

Figure 1. Simplified Vaccine Cold-Chain Distribution Network

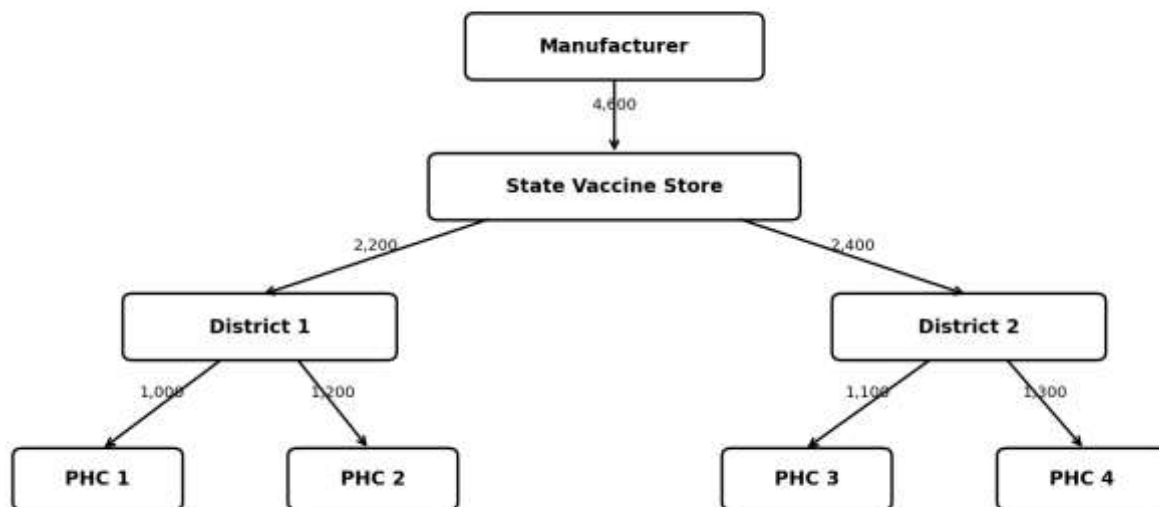


Figure 1. Simplified vaccine cold-chain distribution network used in the model.

The network contains one manufacturer, one state vaccine store, two district stores and four primary health centres (PHCs). All values used in the model are illustrative and are intended to demonstrate the Operations Research methodology rather than represent an actual vaccine distribution network.

4.2 Model Parameters

Parameter	Value
Manufacturer supply	5,000 doses
PHC 1 demand	1,000 doses
PHC 2 demand	1,200 doses
PHC 3 demand	1,100 doses
PHC 4 demand	1,300 doses
District 1 capacity	2,500 doses
District 2 capacity	2,500 doses
Vehicle capacity	500 doses/trip
Vehicle-trip cost	₹500/trip
Shortage penalty	₹20/dose
Route	Cost per Dose
Manufacturer → State Store	₹1.00
State Store → District 1	₹1.50
State Store → District 2	₹1.20
District 1 → PHC 1	₹0.80
District 1 → PHC 2	₹0.90
District 2 → PHC 3	₹0.70
District 2 → PHC 4	₹0.85

4.3 Decision Variables

The main decision variable, x_{ij} , represents the number of vaccine doses transported from node i to node j . A shortage variable, s_j , represents doses that are not supplied to PHC j . An integer variable, n_{ij} , represents the number of refrigerated vehicle trips required on route $i-j$.

4.4 Objective Function

$$\text{Minimize } Z = \sum c_{ij}x_{ij} + \sum P_j s_j + \sum 500n_{ij}$$

The first term captures transportation costs, the second represents the penalty for shortages and the third captures the cost of refrigerated vehicle trips.

4.5 Constraints

1. Supply constraint: quantity dispatched from the manufacturer cannot exceed 5,000 doses.
2. State-store flow balance: doses entering the state store must equal doses sent to the two district stores.
3. District flow balance: doses entering each district must equal doses sent from that district to its assigned PHCs.

4. District capacity constraints: each district store cannot handle more than its capacity.
5. PHC demand constraints: doses received plus shortage must equal the demand of each PHC.
6. Vehicle capacity constraints: flow on each route cannot exceed 500 doses multiplied by the number of vehicle trips.
7. Non-negativity: vaccine flows and shortage variables must be non-negative.
8. Vehicle-trip variables are restricted to integer values.

4.6 Problem Type and Solution Method

The model is a capacitated network-flow/transportation optimization problem. Since the number of refrigerated vehicle trips is an integer decision, the complete formulation is a mixed-integer linear programming (MILP) model. Microsoft Excel Solver is used to obtain the solution, with the Simplex LP method and integer restrictions on the vehicle-trip variables.

In the Excel implementation, the objective cell combines route transportation costs, refrigerated vehicle-trip costs and shortage penalties. The decision cells contain the route flows, shortage quantities and integer vehicle-trip variables. The final Solver formulation applies the supply, district-capacity, flow-balance, PHC-demand, vehicle-capacity and integrality constraints together.

4.7 Assumptions

- Supply and demand are known and deterministic for the planning period.
- A single vaccine is considered.
- The cold chain is assumed to be maintained throughout transportation.
- Transportation costs are fixed for each route.
- Vehicle capacity is fixed at 500 doses per trip.
- Shortages are permitted and are assigned a penalty cost.
- Only the routes specified in the model are available.
- The model represents a single planning period and does not include inventory carried across periods.

5. Results and Analysis

5.1 Base-Case Results

The Excel Solver model distributes 4,600 doses, which exactly matches total PHC demand. The remaining 400 doses from the manufacturer's 5,000-dose supply are therefore not needed during the current planning period.

Route	Optimal Flow	Vehicle Trips	Transport Cost	Vehicle Cost
Manufacturer → State Store	4,600	10	₹4,600	₹5,000
State Store → District 1	2,200	5	₹3,300	₹2,500
State Store → District 2	2,400	5	₹2,880	₹2,500
District 1 → PHC 1	1,000	2	₹800	₹1,000
District 1 → PHC 2	1,200	3	₹1,080	₹1,500
District 2 → PHC 3	1,100	3	₹770	₹1,500
District 2 → PHC 4	1,300	3	₹1,105	₹1,500
Total	4,600	31	₹14,535	₹15,500

Total transportation cost = ₹14,535

Total refrigerated vehicle-trip cost = ₹15,500

Shortage cost = ₹0

Total distribution cost = ₹30,035

The solution satisfies every PHC demand without a shortage. District 1 receives 2,200 doses, which are then allocated as 1,000 doses to PHC 1 and 1,200 doses to PHC 2. District 2 receives 2,400 doses, allocated as 1,100 doses to PHC 3 and 1,300 doses to PHC 4.

5.2 Sensitivity Analysis

Scenario	Supply	Demand Change	Vehicle Capacity	Vehicle Cost	Total Cost	Shortage Cost
Base Case	5,000	0%	500	₹500	₹30,035	₹0
Supply Reduction	4,000	0%	500	₹500	₹36,650	₹12,000
Demand Increase	5,000	+10%	500	₹500	₹34,361.50	₹2,800

Higher Vehicle Cost	5,000	0%	500	₹750	₹37,785	₹0
Lower Vehicle Capacity	5,000	0%	400	₹500	₹33,035	₹0

The sensitivity analysis shows that a reduction in supply from 5,000 to 4,000 doses creates a shortage cost of ₹12,000. A 10% increase in demand results in a shortage cost of ₹2,800. Increasing the vehicle-trip cost from ₹500 to ₹750 raises total cost to ₹37,785 without creating a shortage, while reducing vehicle capacity from 500 to 400 doses per trip raises total cost to ₹33,035.

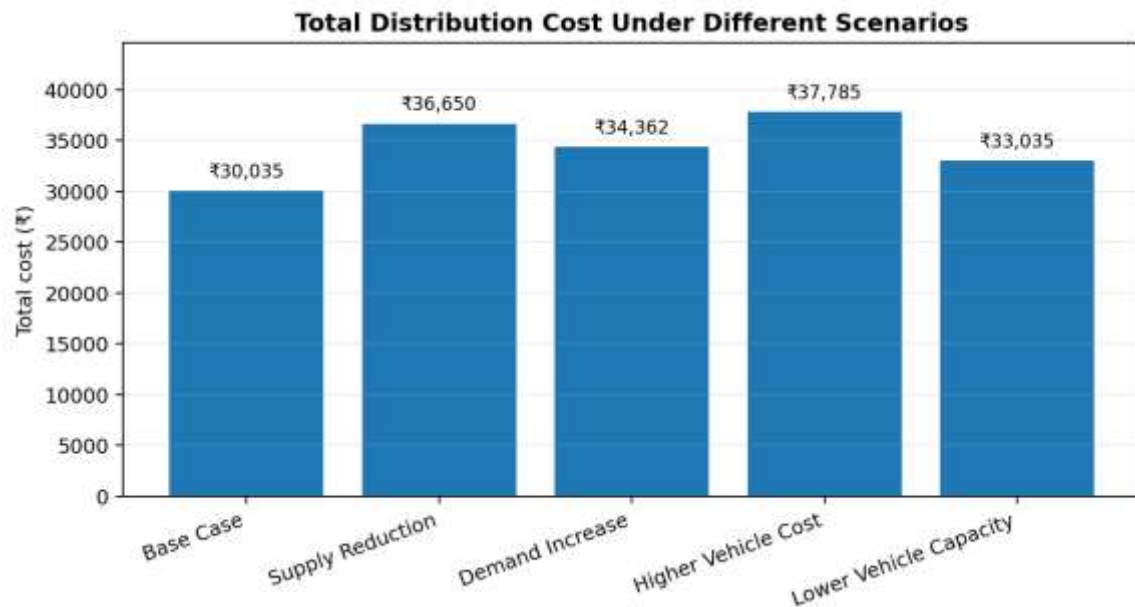


Figure 2. Total distribution cost under the sensitivity scenarios.

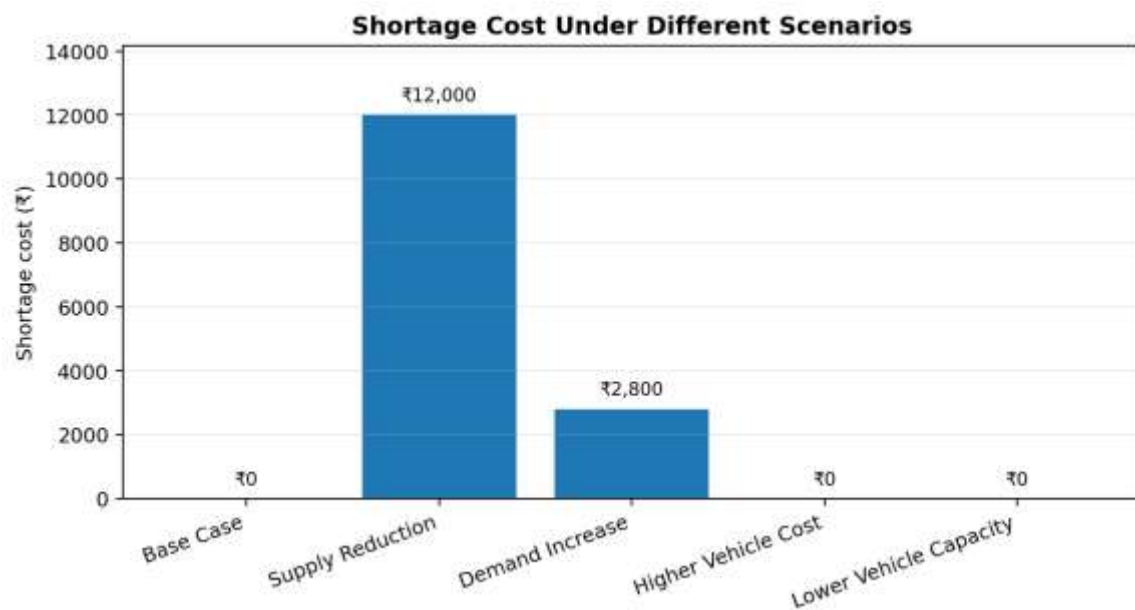


Figure 3. Shortage cost under the sensitivity scenarios.

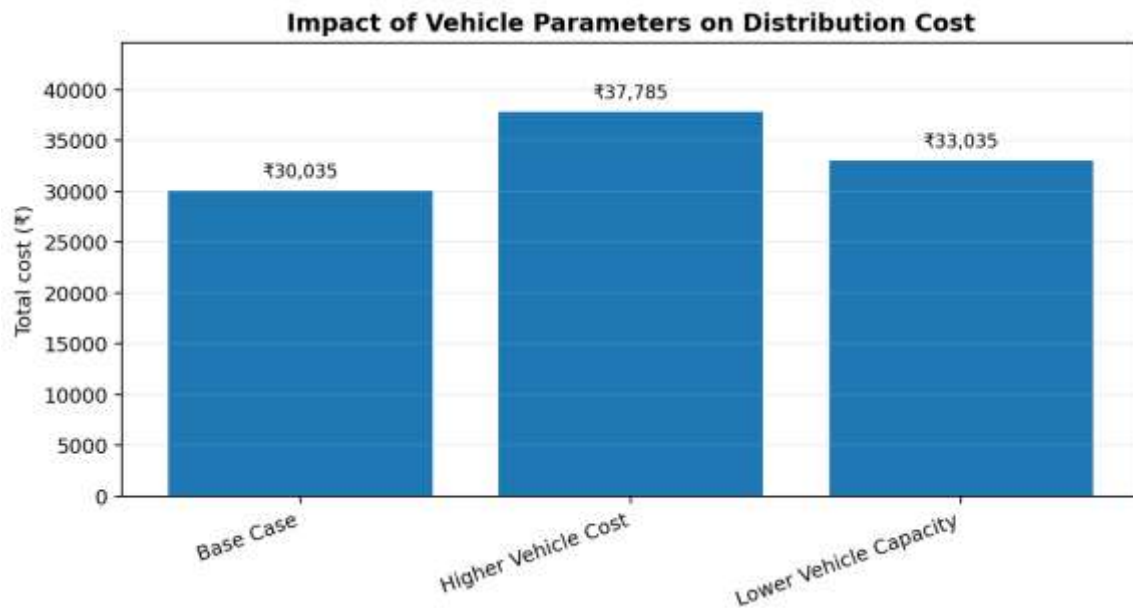


Figure 4. Impact of vehicle-related parameters on total distribution cost.

Note: All scenario values are based on the illustrative assumptions defined in the Excel Solver model; they are used to demonstrate the optimization methodology and are not claimed to represent an actual vaccine distribution network.

5.3 Overall Findings

In the base case, the model satisfies all 4,600 doses of demand without shortages while respecting district and vehicle capacities. The sensitivity analysis also shows that supply reductions and demand increases can create shortages, whereas changes in vehicle-related parameters can increase cost even when all demand continues to be satisfied.

6. Critical Analysis and Discussion

6.1 Strengths of the Model

The model gives a clear representation of a multi-tier vaccine distribution network, showing how vaccines move from the manufacturer through the state and district levels to healthcare facilities. It includes transportation cost, refrigerated vehicle-trip cost and shortage cost, while the capacity constraints and integer vehicle-trip decisions make the model more representative of an actual distribution decision.

Another advantage is that the model is implemented in Excel Solver. This makes the formulation relatively easy to understand, modify and test without requiring specialized optimization software.

6.2 Limitations of the Model

The model is still a simplified representation of an actual vaccine supply chain. Supply and demand are treated as deterministic, even though both can change in practice. The model also covers only one planning period and does not include inventory carried between periods, delivery lead times or vaccine expiry.

Cold-chain reliability is not explicitly modelled. The model assumes that vaccines remain within the required temperature range, whereas Lin et al. (2020) consider transportation-mode choice, equipment malfunction, temperature-recording malfunction and potential losses associated with vaccine quality.

The model also uses fixed route costs and considers only one vaccine type. Real distribution networks may involve alternative routes, several vaccine types and additional operational restrictions.

6.3 Comparison with the Literature

Lin et al. (2020) focus mainly on the decision between cold-chain and non-cold-chain transportation and incorporate vaccine quality, cold-chain cost, equipment and temperature-monitoring failures, retailer trust and potential losses. The present model assumes that the cold chain is already established and instead focuses on how vaccines should be allocated through the network.

Sripada et al. (2023) develop a more comprehensive multi-tier vaccine distribution framework that includes inventory, transportation quantities, vehicle requirements, shortages, facility selection and healthcare personnel. The present model simplifies these decisions and concentrates on transportation flows, vehicle capacity and shortages.

The model developed in this project should therefore be viewed as a simplified application of the optimization concepts found in the literature, rather than as a reproduction of either paper's full formulation.

6.4 Possible Improvements and Extensions

- Uncertainty: Demand and supply could be treated as uncertain using stochastic programming or robust optimization.
- Multi-period planning: Inventory, replenishment decisions and delivery lead times could be incorporated.
- Vaccine expiry: Shelf-life constraints could be added to reduce wastage from expired doses.
- Cold-chain failure risk: Temperature excursions, refrigeration failure and monitoring-system failures could be incorporated.
- Multiple vaccines: Several vaccines with different storage and demand requirements could be optimized simultaneously.
- Real geographical data: Actual distances and route-specific transportation costs could replace illustrative values.
- Environmental considerations: Fuel consumption and carbon emissions could be included alongside financial costs.

6.5 Overall Discussion

The developed model shows how Operations Research can turn a complex vaccine distribution problem into a structured mathematical optimization problem. In the base case, all PHC demand is satisfied without shortages at a total cost of ₹30,035. The sensitivity analysis shows that changes in supply, demand and vehicle parameters can have a meaningful effect on both cost and feasibility.

The analysis also shows why a simple transportation-cost calculation is not enough for a realistic vaccine distribution problem. More advanced models could incorporate uncertainty, inventory, vaccine quality and other operational decisions.

7. Conclusion

Vaccine distribution is an important real-world application of Operations Research because it combines limited resources, multiple distribution stages, capacity restrictions and the need for reliable access to vaccines.

This project examined two studies on vaccine cold-chain optimization and used their main ideas to develop a simplified mathematical model. The model represents vaccine movement from a manufacturer through a state vaccine store and district stores to four primary health centres. It minimizes transportation cost, vehicle-trip cost and shortage cost subject to supply, capacity, demand and vehicle-capacity constraints.

In the base case, the model satisfies total demand of 4,600 doses without shortages at a total cost of ₹30,035, consisting of ₹14,535 in transportation costs and ₹15,500 in vehicle-trip costs. The sensitivity analysis shows that reductions in supply and increases in demand can create shortages, while changes in vehicle-related parameters can raise total distribution cost.

Overall, the project demonstrates how Operations Research can provide a systematic decision-support approach to vaccine distribution. Even a simplified optimization model can help evaluate allocation decisions and the effect of operational changes. More advanced formulations can build on this foundation by incorporating the additional complexities found in real-world cold-chain networks.

8. References

- Lin, Q., Zhao, Q., & Lev, B. (2020). Cold chain transportation decision in the vaccine supply chain. *European Journal of Operational Research*, 283, 182–195.
- Sripada, S., Jain, A., Ramamoorthy, P., & Ramamohan, V. (2023). A Decision Support Framework for Optimal Vaccine Distribution Across a Multi-tier Cold Chain Network. *Computers & Industrial Engineering*, 182, 109397.