

Multi-Objective Optimization of Cold Chain Visibility and Risk Mitigation for Vaccine Distribution

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Abstract

Cold-chain vaccine distribution often suffers from limited visibility and high supply chain risks due to uncertain demand, dynamic environments, and operational constraints. These challenges make it difficult to ensure timely delivery, maintain product integrity, and control operational costs, highlighting the need for a structured approach to address these uncertainties and improve overall system performance. In response to this need, this research investigates the integration of Supply Chain Visibility (SCV) and Supply Chain Risk (SCR) in cold-chain vaccine distribution using a fuzzy multi-objective decision-making framework. Real-world data from Bangladesh, including demand, capacity, and operational constraints were utilized to validate the proposed research. Based on this datasheet, a multi-objective integer programming model was developed to simultaneously maximize SCV, minimize SCR, and reduce overall cost. The model uses fuzzy triangular numbers to capture uncertainties in demand, visibility, and risk. Furthermore, a Genetic Algorithm (GA) is employed to find optimized solutions. The obtained results demonstrate that, enhancing visibility while mitigating supply chain risks significantly improves operational performance, with SCV increased by 21%, SCR reduced by 2%, and the optimal cost decreased by BDT 175 million. Overall, this research offers a practical decision support tool for efficient cold-chain vaccine distribution in developing countries.

Keywords

Supply Chain Visibility; Supply Chain Risk; Cold Chain Logistics; Fuzzy Optimization; Genetic Algorithm.

1. Introduction

Efficient distribution of vaccines requires a reliable cold-chain supply system to ensure that temperature-sensitive products maintain efficacy from manufacturers to end users. The COVID-19 pandemic has highlighted the critical

importance of such systems, as vaccines like mRNA-based formulations must be stored and transported at very low temperatures to remain effective (Corey et al. 2020). Uncertainties in demand, limited storage capacity, and transport conditions increase the risk of spoilage and operational inefficiencies, particularly during mass immunization campaigns. Real-time monitoring and robust risk management are essential to ensure safe and timely delivery of vaccines to populations worldwide. Visibility in the supply chain is critical for the success of multinational corporations and for successful supply chain management and logistics operations. It involves supply chain executives and experts sharing information on supply chain strategies and partner practices (Francis 2008). In the context of vaccinations, supply chain visibility involves the sharing of pertinent and useful information in addition to the interchange of data on supply chain activities (Caridi et al. 2014). It is important to ensure the accuracy, credibility, suitability, and utility of the exchanged information, and documenting the supply chain processes which is most affected by visibility. (Kaipia and Hartiala 2006; Johnson and Sohi 2001). Cold-chain visibility (SCV) provides supply chain managers with accurate information on inventory, location, and condition of shipments, while Supply Chain Risk (SCR) accounts for potential disruptions, including temperature deviations, handling errors, or transport delays. During the COVID-19 vaccine rollout, lapses in visibility or risk management could result in significant vaccine losses and compromise immunization efforts. Integrating SCV and SCR into operational decision-making is therefore critical for vaccines requiring strict temperature maintenance. As shown, vaccine shipments are plagued by multiple issues. Effective vaccine shipment requires cold supply chain visibility and risk reduction. Supply chain visibility tracks goods and products in shipments, showing the catalog and activity. Carriers may regain customer facilities and control costs through inventory management, active status updates, risk mitigation, and distraction reduction. With excellent visibility, the supply chain becomes more responsive. Supply chain visibility improves supply chain intelligence and reduces risk. By using these insights alongside user data, firms can create an effective supply chain. For instance, shippers can improve customer service, save expenses, and strengthen their supply chains. A solid risk mitigation strategy helps firms avoid, mitigate, or decrease hazards. These methods provide reliable data and reduce vaccination provider risk (Radanliev et al. 2021).

This study addresses a key research gap by integrating fuzzy modeling, SCV, SCR, and multi-objective optimization into a unified framework for cold-chain vaccine distribution. While existing research has significantly advanced cold-chain logistics, most studies examine isolated components such as demand uncertainty, environmental challenges, IoT-based monitoring, or routing optimization without combining them into a comprehensive model. Only a limited number of studies incorporate uncertainty modeling, SCV, SCR, environmental considerations, multi-objective optimization, and fuzzy logic together. Therefore, the authors intended to address the following objectives in this study: (1) To develop a fuzzy multi-objective optimization model to maximize supply chain visibility and minimize supply chain risk while controlling operational costs in vaccine distribution; (2) To implement and compare Trend analysis and Genetic Algorithm (GA) methods to identify the most effective approach for cold-chain optimization; (3) To assess how improvements in visibility and risk mitigation impact overall operational performance.

2. Literature Review

Today cold chain has come a long way since those early days of transporting goods from one state to another and between attached countries. Technology has made global shipping much more ordinary, and the cold chain has shadowed suit. The pharmaceutical industry has profited from both technology and the cold chain, and we are seeing more and more pharmaceutical shipments stirring internationally. The cold chain confirms the safe, dependable transport of those pharmaceutical shipments, and companies like Cold chain packing and Logistics packing are at the forefront of cold chain technology. Cold chain logistics are essential for transporting temperature sensitive products such as vaccines, biologics, and pharmaceuticals. These systems face uncertainty in demand, transportation delays, limited storage capacity, and product perishability, which makes designing an effective distribution network complex. Sripada et al. (2021) developed a multi period decision support model for vaccine distribution that considers inventory, transportation, storage constraints, and demand fluctuation. Recent studies further extend this work. Chen et al. (2025) proposed a sustainable and resilient vaccine cold chain network model that uses distributional robust optimization. Their model includes economic cost, environmental impact, social resilience, and waste management. They applied the model to influenza vaccine distribution and demonstrated how robust optimization can improve performance under uncertain transportation cost, storage conditions, and vaccine waste. These studies show that vaccine cold chain logistics must balance several objectives including cost, capacity, demand variation, perishability, uncertainty, and environmental concerns. This creates a strong justification for using multi-objective and uncertainty-based optimization models (Chen et al. 2025). Cold chain risk goes beyond demand and storage limitations. Packaging quality, handling errors, environmental exposure, and temperature deviation are major contributors to product damage. Ren and Matellini (2024) introduced a fuzzy Bayesian network model to assess cold chain packaging, transportation, and monitoring risks. Ren (2024) extended this work using fuzzy Bayesian analysis combined with TOPSIS to evaluate container

risk, handling risk, and environmental risk in cold chain shipping. Environmental sustainability also plays an important role. Some studies included carbon emissions, waste generation, and environmental safety in their network design model. This showed that cold chain risk management requires more than operational reliability and should also consider environmental and public health impacts (Chen et al. 2024).

Real time temperature visibility and continuous monitoring are necessary to maintain vaccine quality. Digital technologies such as IoT, AI, sensors, and blockchain are now widely used to improve traceability and quick decision making. Nozari et al. (2024) developed an AIoT based cold chain model that reduces transportation cost and improves product quality through real time sensor data. Jiang et al. (2024) proposed an IoT based framework for sustainable vaccine cold chain management that helps reduce spoilage and improves environmental control. Cold Net, a system that uses IoT devices and blockchain smart contracts to create secure and transparent vaccine tracking (J.L.Vilas Boas et al. 2025). The complexity of vaccine supply systems requires models that can handle multiple objectives such as cost, environmental impact, risk, visibility, and uncertainty. A robust optimization model was explored for multi vaccine and multi-level supply chains considering demand fluctuation, inspection errors, and wastage rates. Chen et al. (2024) used distributional robust optimization to jointly address cost, resilience, emissions, and vaccine waste. Chen et al. (2025) developed a vehicle routing model that considers uncertainty and time varying transport networks to improve cold chain delivery routes. These studies show that modern cold chain optimization relies on robust, multi objective, and uncertainty aware models. This supports the use of fuzzy multi objective optimization and genetic algorithms in real cold chain decision making.

3. Methodology

The study employed a fuzzy multi-objective optimization approach to jointly address supply chain visibility, supply chain risk, and operational cost. Trend-based data analysis and GA were used to generate and compare optimal solutions under real-world constraints. Python, LINGO, and Google Colab were utilized to model the system, solve the optimization problem, and validate numerical outputs. This combined methodological framework enabled both baseline evaluation and enhanced optimization of the cold-chain system.

3.1 Cold Chain Packing & Logistics Passive Packaging System

Cold Chain Packing & Logistics provides various cost-effective solutions, ranging from dry ice shippers to high-performance systems employing phase change materials and vacuum insulation components designed to be user-friendly, readily accessible, and capable of producing any temperature-sensitive cargo. With our delivery technologies, pharmaceutical businesses may supply globally vital vaccinations, medications, illustrations, and more with precision and reliability (Defraeye et al. 2015). Cold Chain Packing & Logistics Passive Packaging Systems can withstand steady stress at ambient temperatures of +30°C while keeping temperature-sensitive goods frozen, making them ideal for most applications and environments (Figure 1).

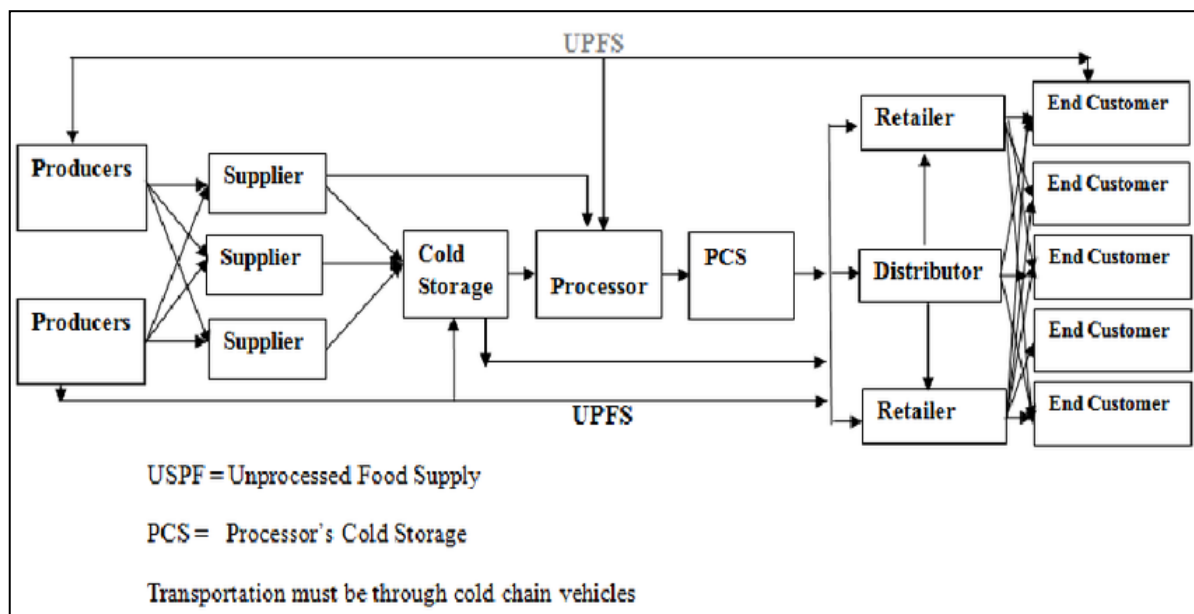


Figure 1. Cold Supply Chain Process

3.2 Steps Involved in the Study

Step 1: Literature review: Many journals, books, periodicals, thesis papers, and articles were read in addition to visiting a variety of websites in order to obtain all the essential data for this thesis. This part consists of reading materials that enhance our understanding of the connected subject.

Step 2: Data collection through different sources: Bangladesh Department of Health (BOH) COVID-19 Data Dewdrop is the primary data source for this research. In addition, the published papers from Bangladesh Statistics Authority (BSA), such as The Women & Men in National Capital Region: 2018 Statistical Handbook First Edition, NCR Gender Factsheet, and 2020 RSET NCR, were used in the same manner for the vaccine distribution model. This research focused on Dhaka, Bangladesh, since it is one of the known "coronavirus hotspots" in Bangladesh.

Step 3: Model development for SCV and SCR: A mathematical model incorporating SCV and SCR is constructed to choose the optimum distributor. The suggested multiple-objective integer programming models have three objectives: maximizing visibility, minimizing risk, and minimizing cost.

Step 4: Solution for GA model: The solution algorithm for the GA model is presented as follows: Build the model using the provided SCV and SCR information. Demand and capacity limitations for various vaccinations and distributors are determined.

Resolve the issue as a single objective problem, including all objective functions. Find the upper and lower limit max-min method for every objective function. Since the SCV and SCR are treated as fuzzy triangular integers (L, M, U), the implementation could be solved the upper and lower-bound solutions.

Where, L (Lower bound) - the smallest possible value of the fuzzy number.

M (Most likely) -the value that is most probable or the peak of the triangle.

U (Upper bound) -the largest possible value of the fuzzy number.

3.3 Mathematical Model Formulation

Notations, i = index of distributor, j = index of vaccine

Decision variables,

Q_{ij}	quality of vaccine i provided by distributor j ,
Y_{ij}	a binary variable determined by whether vaccine j is supplied by distributor i ,
Y_{ij}	$\begin{cases} 1 & \text{if vaccine } i \text{ is supplied by distributor } j, \\ 0 & \text{otherwise.} \end{cases}$

Parameters,

B_i	budget available to enhance SCV for vaccine i ,
C_j	production capacity of distributor j ,
CR_{ij}	cost of reducing supply risk for vaccine i from distributor j ,
CV_{ij}	cost of enhancing SCV to the current level for vaccine i from distributor j ,
D_i	demand for vaccine i ,
M_{ij}	minimum order quantity for vaccine i required by distributor j ,
P_{ij}	purchase price for vaccine i supplied by distributor j ,
IR_{ij}	impact caused by supply risk for vaccine i from distributor j ,
R_{ij}	supply risk for vaccine i from distributor j ,
R_i	maximum allowable supply risk for distributor j ,
V_{ij}	supply chain visibility incurred if vaccine i is supplied by distributor j ,
V_i	minimum amount of visibility needed for vaccine i ,

Objective Functions,

$$\text{Maximize Visibility} = \sum_i \sum_j V_{ij} Y_{ij} \quad (1)$$

$$\text{Minimize Risk} = \sum_i \sum_j R_{ij} Y_{ij} \quad (2)$$

$$\text{Minimize Cost} = \sum_i \sum_j V_{ij} CV_{ij} Y_{ij} + \sum_i \sum_j R_{ij} CR_{ij} + \sum_i \sum_j IR_{ij} Y_{ij} + \sum_i \sum_j P_{ij} Q_{ij} \quad (3)$$

Subject to,

$$\sum_j V_{ij} CV_{ij} Y_{ij} \leq B_i \quad \text{for each } i \quad (4)$$

$$\sum_j V_{ij} Y_{ij} \leq V_i \quad \text{for each } i \quad (5)$$

$$\sum_j Q_{ij} = D_i \quad \text{for each } i \quad (6)$$

$$\sum_j Q_{ij} \leq C_j Y_{ij} \quad \text{for each } j \quad (7)$$

$$\sum_j R_{ij} Y_{ij} \leq R_i \quad \text{for each } i \quad (8)$$

$$Q_{ij} \geq M_{ij} Y_{ij} \quad \text{for each } i, j \quad (9)$$

$$Q_{ij} \leq N Y_{ij} \quad \text{for each } i, j \quad (10)$$

$$Q_{ij} \geq 0 \quad \text{for each } i, j \quad (11)$$

$$Y_{ij} = 0 \text{ or } 1 \quad \text{for each } i, j \quad (12)$$

Constraint (4) limits the spending of SCV under a planned budget for all distributors. Constraint (5) implements the minimum amount of visibility for each vaccine. Constraint (6) enforces the contentment of the demand quantity for each vaccine. Constraint (7) serves as the capacity constraint for each distributor. Constraint (8) limit the maximum allowable supply risk for each vaccine supplied by all distributors. Constraint (9) specifies the minimum order quantity of each vaccine for all distributors. Constraint (10) avoids a conflict of the decision variables where N is relatively large. Constraint (11), while redundant, preserves the non-negativity, and Constraint (12) maintains the integrality of the decision variables.

3.4 Data for Trend Analysis and GA Method

In this study, two types of numerical inputs -Trend data and GA data were used to examine how SCR and SCV influence cold chain performance. The Trend data represent existing operational patterns of the cold chain, while the GA data represent optimized values generated through the model to minimize SCR and maximize SCV. The parameters used include budget, cost, risk cost, visibility cost, demand, manufacturing capacity, price, inventory risk, and several decision variables. These values serve as the key inputs to the mathematical model and were incorporated into the Python and LINGO programming environment to execute the multi-objective function developed for this study. Python was used for data preprocessing, simulation, and implementing the fuzzy multi-objective optimization model. LINGO was used to solve the mathematical optimization model, particularly for validating results from the fuzzy multi-objective integer programming model. Google Colab was used as a cloud-based platform to execute Python scripts, enabling collaboration, easy sharing, and access to high-performance computing resources. It supports seamless integration with Python libraries and facilitates reproducible results without local installation constraints. Trend data are given in **Table 1**.

Table 1. Data for Trend Analysis and GA Method

Methods	Parameters											
	B _i	C _j	CR _{ij}	CV _{ij}	D _i	M _{ij}	P _{ij}	IR _{ij}	R _{ij}	R _i	V _{ij}	V _i
Trend	0.2	1	0.05	400	0.9	0.1	500	1	3	5	8	1
GA	0.3	2	0.06	100	1	0.2	600	2	3	5	12	1

4. Data Analysis and Findings

This section presents the analytical interpretation of how SCV and SCR influence cold chain performance based on the model outcomes. SCV enables faster and more accurate communication regarding product demand, inventory levels, transport conditions, and logistical status. Higher visibility helps decision-makers anticipate disruptions and adjust resource allocation accordingly. Conversely, SCR represents the likelihood of unfavorable events-such as temperature excursions, delays, or handling failures that adversely impact cold chain reliability. Using the developed fuzzy multi-objective model, the study analyzed how SCV and SCR behave under different

operational conditions. The analytical model revealed clear improvements in SCV and contribute to faster detection of deviations, whereas reductions in SCR minimize bottlenecks and failures in product integrity. The Trend data showed the existing performance of the cold chain, while the GA-generated data provided enhanced parameter sets obtained through optimization. Comparison of the two data sets helped determine how much improvement could be achieved by reducing risk factors and increasing SCV. The findings indicate that addressing SCR is a priority before attempting visibility enhancements, as risk reduction directly stabilizes the operational environment needed for visibility-based improvements.

5. Result and Discussion

The result was found for the trend method using the function created with the help of Python, LINGO, and Google Colab. Then this preparable data was used to get the visualized result using the GA method and cross-checked to find the perfect result that we visualized to mitigate supply chain risk and increase supply chain visibility. While this study primarily focuses on SCV and SCR, temperature risk is indirectly mitigated through visibility higher SCV allows real-time tracking cold-chain shipments, enabling early corrective actions in case of temperature deviations. For visualizing the Trend and GA results, comparison bar carts for every result have been shown in **Figure 2**.

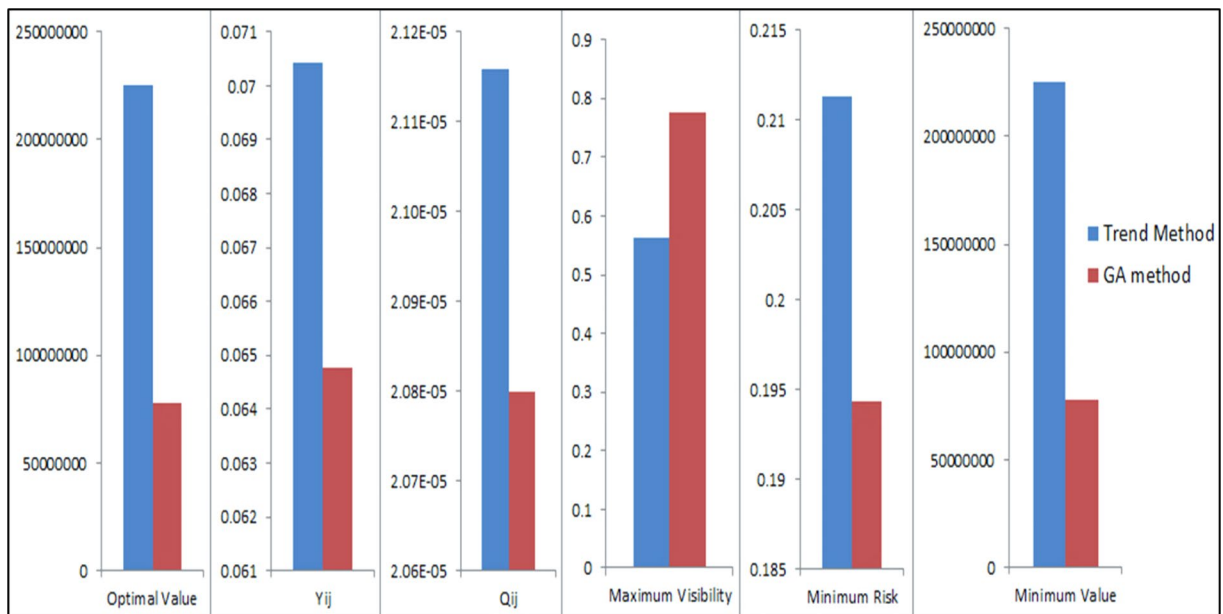


Figure 2. Result Visualization of Trend and GA Method

5.1 Comparison of Trend Analysis and GA Method

The Trend analysis with general trend data showed that the maximum supply chain visibility reached 56%, while minimum supply chain risk was 21%. The optimal value generated in this method was relatively higher, indicating less efficiency. On the other hand, the GA method produced more promising results. With the same dataset, the GA method achieved 77% supply chain visibility and 19% supply chain risk, while also generating a lower optimal value, indicating greater efficiency in solving the optimization problem (Table 2).

Table 2. Comparison of Trend Analysis and GA Method

Parameters	Trend, %	GA, %	%Difference
Supply Chain Visibility	56	77	+21
Supply Chain Risk	21	19	-2
Optimal Cost (millions, BDT)	225	50	-175

From **Figure 2**, significant difference between the two methods can be observed where the GA method outperformed the Trend method in several key aspects. The GA method reduced supply chain risk from 21% to 19%, a 2% decrease, indicating a more robust and stable supply chain. Visibility increased significantly from 56% to 77% using GA a 21% improvement. Higher visibility indicates better traceability, improved decision-making, and greater responsiveness within the cold chain system. The GA method produced a lower optimal cost from BDT 225 to 50 million. A lower optimal value suggests improved efficiency in resource utilization and logistical planning. Based on all comparative indicators, the GA method demonstrates superior performance. It enhances visibility, reduces supply chain risks, and produces more optimal computational results. Therefore, the GA method can be considered more effective and reliable for cold chain supply chain optimization compared to the Trend method.

6. Conclusions and Recommendations

This study presents a fuzzy multi-objective optimization framework for cold-chain vaccine distribution, balancing SCV, SCR, and cost. GA provides superior performance over baseline methods in both visibility and risk metrics. The model is applicable for real-world data, offering a practical decision-support system for vaccine distribution in developing countries. SCV enables fast and accurate communication of demand, quantity, inventory location, transportation cost, and other operational parameters, while SCR represents the likelihood of disruptive events affecting supply chain performance. Considering the multi-layered structure of decision-making, with multiple stages and stakeholders, this study adopts a fuzzy multi-objective approach to model SCV and SCR from an operational perspective. The model integrates SCV maximization, SCR minimization, and cost minimization under budget, demand, production capacity, and supply availability constraints. To highlight the core contributions of this research, the study successfully establishes the following:

- A fuzzy multi-objective optimization model was developed to simultaneously maximize supply chain visibility and minimize supply chain risk while controlling operational costs.
- Trend and GA methods were implemented and compared, demonstrating that GA outperforms the Trend method by increasing SCV by 21%, reducing SCR by 2%, and decreasing the optimal cost by BDT 175 million.
- The improvements in visibility and risk mitigation were shown to enhance overall operational performance, resulting in better traceability, responsiveness, and efficiency across the cold-chain system.

A considerable scope for further development remains. Future work can incorporate larger datasets and advanced predictive analytics using data science techniques. Beyond fuzzy logic, alternative optimization approaches may offer even more effective solutions. Scenario analysis can support future disruptions, while integrating IoT sensors for real-time visibility can enhance system responsiveness. Expanding the model to multi-city or national-scale networks and including environmental impacts such as low-carbon logistics would strengthen sustainability. Due to limited data, some assumptions were necessary, emphasizing the need for more structured and critical data collection. Incorporating machine learning and advanced forecasting algorithms may help generate stronger predictive accuracy and more efficient cold-chain network designs in the future.

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