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Prioritizing Resilient Vaccine Distribution Strategies: A BWM-TOPSIS Multi-Criteria Decision-Making Framework

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ABSTRACT

Vaccine distribution is a logistics-intensive public-health function in which product quality, coverage, timeliness, and equity depend on the interaction between cold-chain capacity, transportation reliability, data visibility, institutional coordination, and last-mile service delivery. In countries where infrastructure and governance arrangements are uneven across regions, vaccine logistics cannot be improved through a single technical intervention. It requires a structured decision process capable of prioritizing the criteria that matter most and identifying improvement strategies that offer the highest overall contribution to system resilience. This paper develops a multi-criteria decision-making framework for prioritizing resilient vaccine distribution strategies in Libya. The framework combines the Best Worst Method (BWM), used to derive criteria weights from expert judgments, with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), used to rank five improvement strategies. Eight logistical criteria are considered: cold-chain equipment and storage capacity, temperature monitoring and data visibility, transportation accessibility and fleet reliability, power reliability and backup energy, inventory management and wastage control, human resources and SOP compliance, institutional coordination and emergency preparedness, and equity of last-mile coverage. The BWM results assign the highest weights to cold-chain equipment and storage capacity, power reliability and backup energy, transportation accessibility, and temperature monitoring. TOPSIS ranks upgrading cold-chain equipment and backup power as the most preferred strategy, followed by developing regional hubs with route optimization. Sensitivity analysis indicates that the leading strategy remains stable under alternative weighting scenarios. The proposed framework offers a transparent decision-support tool for health authorities and development partners seeking to strengthen vaccine supply-chain resilience in Libya and similar fragile or infrastructure-constrained settings.

1. Introduction

Vaccination programs are among the most cost-effective public-health interventions, yet their impact depends not only on vaccine availability but also on the reliability of the systems that receive, store, transport, monitor, and deliver vaccines to eligible populations [1]. A vaccine may lose effectiveness if temperature requirements are violated, if inventories are not accurately monitored, or if final delivery points cannot be reached within appropriate time windows [2]. For this reason,

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vaccine distribution is considered a complex logistics system that links national warehouses, regional stores, municipal health offices, primary health-care facilities, outreach teams, transport providers, data systems, and community-level demand [3, 4].

The logistics challenge is particularly important for vaccines because most products are temperature-sensitive biological materials [5, 6]. International immunization guidance emphasizes the need for adequate cold-chain equipment, temperature monitoring, safe storage, accurate stock management, trained personnel, and emergency procedures [7]. The World Health Organization maintains dedicated vaccine-management guidance and tools covering essential immunization supply-chain practices, while UNICEF procurement guidance stresses that a fully functional cold-chain system is a precondition for receiving, storing, and delivering vaccines safely [8]. These requirements become more difficult to meet when electricity supply is unstable, transport networks are uneven, and health facilities differ in operational readiness.

Recent global and regional experience has also shown that vaccine supply chains need resilience, not only efficiency [9, 10]. The COVID-19 pandemic exposed weaknesses in forecasting, procurement coordination, ultra-cold and standard cold-chain capacity, real-time stock visibility, and last-mile distribution [11, 12]. Beyond emergency vaccination, routine immunization programmes face the persistent problem of zero-dose and under-vaccinated children [13]. UNICEF reported that the Middle East and North Africa region experienced a decline in DTP1 coverage compared with pre-pandemic levels, warning that gaps in immunization coverage increase the risk of vaccine-preventable disease outbreaks [14]. Although national averages are useful, they may hide substantial subnational inequities in access and service continuity.

The literature on vaccine logistics has expanded in several directions. One stream focuses on optimization models for multi-echelon cold-chain networks, route planning, inventory costs, shortages, and uncertainty [15, 16]. A second stream examines digital monitoring, blockchain-based traceability, Internet-of-Things temperature monitoring, and automated alerts [17]. A third stream evaluates managerial and institutional factors such as staff training, coordination, emergency planning, and service coverage [18]. These studies provide valuable modelling and technological contributions, but many of them require detailed operational datasets that are not always available in fragile or institutionally fragmented settings. In such contexts, expert-based decision models remain useful because they can structure qualitative and semi-quantitative knowledge into defensible priorities [19].

Multi-criteria decision-making (MCDM) methods are well suited to this type of problem [20]. Vaccine distribution decisions involve multiple criteria that cannot be reduced to cost alone. A strategy that is inexpensive may have limited effect on equity; a technology-based intervention may improve visibility but fail if staff are not trained; and expanding cold-chain capacity may not improve coverage if transport and outreach remain weak. MCDM methods allow decision makers to account for such trade-offs and to combine technical, operational, institutional, and social dimensions in a systematic way [21]. They also make the decision process more transparent because criteria, expert judgments, weights, scores, and rankings are explicitly reported [19].

Libya provides a relevant case for applying such a framework. The health system has faced persistent challenges related to political instability, fragmented information systems, service-delivery disparities, infrastructure limitations, and emergency preparedness needs [22, 23]. WHO's 2024 Libya annual report refers to fragmented health information systems, outdated infrastructure, and the need for digital health transformation, while WHO's 2025 support to Libya's national immunization review explicitly included leadership and governance, programme management, service delivery, cold-chain logistics, disease surveillance, community outreach, and data quality [24]. UNICEF has also reported support for strengthening Libya's immunization system through cold-chain expansion, vaccine safety, outbreak response, and efforts to reduce zero-dose children in high-risk municipalities.

The aim of this paper is to develop and demonstrate a BWM-TOPSIS decision framework for prioritizing resilient vaccine distribution strategies in Libya. The specific objectives are to identify a concise set of logistical criteria relevant to vaccine distribution, derive their relative importance using BWM, evaluate a limited set of feasible improvement strategies using TOPSIS, and discuss the implications for public-health logistics planning.

2. Methodology

This study suggests an MCDM framework. First, the decision problem is formulated by defining the goal, criteria, and improvement strategies. Second, expert judgments are collected to determine the relative importance of the criteria using BWM method. Third, the strategies are assessed against the criteria using a nine-point performance scale. Fourth, TOPSIS method is applied to obtain a final ranking of strategies. Finally, a sensitivity analysis is performed to examine whether the ranking is stable under alternative weighting assumptions.2.1 Best Worst Method.

2.1 Best Worst Method

The Best Worst Method is a pairwise-comparison weighting method proposed by Rezaei [25]. It begins by asking each decision maker to identify the best criterion, meaning the most important criterion for the decision problem, and the worst criterion, meaning the least important criterion. The expert then provides two comparison vectors. The first vector compares the best criterion with each of the other criteria, while the second compares each criterion with the worst criterion. Values are usually expressed on a scale from 1 to 9, where 1 indicates equal importance and 9 indicates extreme preference.

Let $C = \{C1, C2, \ldots\ldots Cn\}$ be the set of criteria. If CB is the best criterion and CW is the worst criterion, the best-to-others vector is AB = (aB1, aB2, ..., aBn), where aBj indicates the preference of the best criterion over criterion j. The others-to-worst vector is AW = (a1W, a2W, ..., anW), where ajW indicates the preference of criterion j over the worst criterion. The objective is to estimate the criteria weights w1, w2, ..., wn such that wB/wj is close to aBj and wj/wW is close to ajW for all j.
The standard linear BWM model can be written as follows:

Minimize ξ, subject to |wB - aBj wj| ≤ ξ and |wj - ajW wW| ≤ ξ for all j, Σwj = 1, and wj ≥ 0.

The optimal value ξ* reflects the level of inconsistency in the expert's comparisons. Smaller values indicate more coherent judgments. In group decision-making, individual BWM weights may be aggregated by arithmetic mean, geometric mean, or another justified aggregation rule.

The BWM has been widely applied in different decision-making contexts because it reduces the number of pairwise comparisons while maintaining a structured and transparent weighting process. In previous studies, the method has been used for supplier selection [20], supply-chain assessment [26], vehicle-routing and logistics optimization [27], and site selection [28]. These applications indicate that BWM is particularly suitable for problems involving expert judgment, multiple conflicting criteria, and the need to derive reliable criteria weights under limited or uncertain data conditions.

2.2 Technique for Order Preference by Similarity to Ideal Solution

TOPSIS is used after the criteria weights have been obtained. The method is based on a simple principle [29]: the preferred alternative should be as close as possible to the positive ideal solution and as far as possible from the negative ideal solution. The positive ideal solution contains the best observed performance value for each criterion, whereas the negative ideal solution contains the worst observed performance value. This makes TOPSIS suitable for ranking vaccine distribution strategies because it considers the relative performance of each strategy across all criteria simultaneously.

Assume that x_{ij} represents the score of strategy i on criterion j and w_j is the BWM weight of criterion j. The TOPSIS procedure used in this paper is summarized in five steps: (1) construct the decision matrix; (2) normalize the matrix using vector normalization; (3) multiply the normalized values by the BWM weights to obtain the weighted normalized matrix; (4) determine the positive and negative ideal solutions; and (5) calculate each strategy's distance from the positive and negative ideals. The closeness coefficient for strategy i is calculated as $CC_i = D_i^- / (D_i^+ + D_i^-)$, where D_i^+ is the distance from the positive ideal and D_i^- is the distance from the negative ideal. A higher closeness coefficient indicates a better-ranked strategy. All eight criteria in this study are treated as benefit criteria because higher performance scores represent stronger contribution to resilient vaccine distribution.

3. Conducted Results

Libya's vaccine distribution system operates in a context marked by regional variation in infrastructure, long distances between population centres, uneven access to remote municipalities, and differing levels of facility readiness. The health system has also been affected by governance fragmentation, information-system limitations, and emergency-response pressures. WHO's support to Libya's national immunization review in 2025 indicates that cold-chain logistics, data quality, community outreach, and service delivery remain central components of the immunization performance agenda [24]. These conditions justify the use of a multi-criteria framework that can prioritize interventions across technical, logistical, institutional, and equity dimensions.

3.1 Criteria

Eight criteria were selected based on immunization supply-chain guidance, the Libya health-system context, and the literature review. The criteria are listed in Table 1.

Table 1.
Criteria used in the proposed BWM-TOPSIS framework

Code	Criterion	Operational definition

C1	Cold-chain equipment and storage capacity	Availability, functional status, and capacity of cold rooms, refrigerators, freezers, vaccine carriers, and related storage equipment across the distribution chain.
C2	Temperature monitoring and data visibility	Ability to record, transmit, and act on temperature and stock information through loggers, digital dashboards, and reporting tools.
C3	Transportation accessibility and fleet reliability	Reliability of transport assets, road accessibility, routing flexibility, fuel availability, and the ability to reach distant municipalities within acceptable delivery windows.
C4	Power reliability and backup energy	Stability of electricity supply and availability of generators, solar refrigerators, voltage protection, and maintenance arrangements.
C5	Inventory management and wastage control	Effectiveness of stock control, reorder planning, expiry-date management, buffer stock policy, and wastage monitoring.
C6	Human resources and SOP compliance	Competence and availability of staff responsible for vaccine handling, storag transport, documentation, and standard operating procedures.
C7	Institutional coordination an emergency preparedness	Coordination between national, regional, municipal, and facility-level actor including contingency planning and emergency response protocols.
C8	Equity of last-mile coverage	Ability of the system to serve remote, underserved, displaced, migrant, an other hard-to-reach populations without compromising timeliness or safety.

3.2 Strategies

Five improvement strategies were defined. Each strategy represents a practical intervention package rather than a single isolated activity.

Table 2
Candidate vaccine distribution improvement strategies

Code	Strategy	Description
S1	Upgrade cold-chain equipment and backup power	Replace obsolete refrigerators and cold rooms, expand storage where capacity is constrained, and add solar or generator-based backup power for priority facilities.
S2	Deploy digital stock and temperature monitoring	Introduce interoperable digital tools for batch tracking, stock visibility, temperature logging, alerts, and reporting across warehouse and facility levels.
S3	Develop regional hubs with route optimization	Create or strengthen regional distribution hubs and redesign routes using demand, distance, storage capacity, and delivery-window constraints.
S4	Strengthen last-mile outreach and dedicated transport	Use dedicated outreach teams, mobile vaccination points, micro-planning, and fit-for-purpose vehicles to improve access in remote and underserved areas.
S5	Improve workforce training and emergency SOPs	Implement repeated competency-based training, supervision, emergency drills, and standard operating procedures for storage, transport, breach response, and inventory practice.

3.3 Expert judgment design

A structured expert-elicitation form was designed for a panel of experts. Each expert selected a best and worst criterion and then completed two comparison vectors. Table 3 reports the best and worst criteria selected by the experts. Tables 4 and 5 provide the corresponding best-to-others and others-to-worst comparison vectors. The scale ranges from 1 to 9, where 1 denotes equal importance and 9 denotes extreme preference.

Table 3
Best and worst criteria selected by the experts

Expert	Best criterion	Worst criterion
E1	C1 - Cold-chain equipment and storage capacity	C6 - Human resources and SOP compliance
E2	C4 - Power reliability and backup energy	C6 - Human resources and SOP compliance
E3	C3 - Transportation accessibility and fleet reliability	C7 - Institutional coordination and emergency preparedness
E4	C1 - Cold-chain equipment and storage capacity	C6 - Human resources and SOP compliance
E5	C2 - Temperature monitoring and data visibility	C7 - Institutional coordination and emergency preparedness

Table 4
Best-to-others comparison vectors

Expert	Best	C1	C2	C3	C4	C5	C6	C7	C8
E1	C1	1	3	2	2	4	7	5	4
E2	C4	2	4	3	1	5	8	5	4
E3	C3	2	3	1	3	4	5	7	4
E4	C1	1	3	3	2	4	7	5	4
E5	C2	2	1	3	3	4	5	7	4

Table 5
Others-to-worst comparison vectors

Expert	Worst	C1	C2	C3	C4	C5	C6	C7	C8
E1	C6	7	5	6	6	4	1	3	4
E2	C6	6	4	5	8	3	1	3	4
E3	C7	6	5	7	5	4	3	1	4
E4	C6	7	5	5	6	4	1	3	4
E5	C7	6	7	5	5	4	3	1	4

3.4 BWM criteria weights

The BWM optimization model was solved separately for each expert, and the resulting individual weights were then aggregated. Table 6 reports the individual weights, the inconsistency value ξ*, and the final aggregated weights. The results indicate that cold-chain equipment and storage capacity (C1) is the most important criterion, followed by power reliability and backup energy (C4), transportation accessibility and fleet reliability (C3), and temperature monitoring and data visibility (C2). This pattern is plausible in the Libyan context because vaccine quality and service continuity depend heavily on both equipment capacity and energy reliability, while geographical access and monitoring capability determine whether vaccines can be delivered safely and transparently to decentralized facilities.

Table 6
Individual and aggregated BWM criteria weights

Expert	C1	C2	C3	C4	C5	C6	C7	C8	ξ*
E1	0.283	0.112	0.168	0.168	0.084	0.033	0.067	0.084	0.053
E2	0.185	0.093	0.124	0.323	0.074	0.034	0.074	0.093	0.048
E3	0.178	0.119	0.300	0.119	0.089	0.071	0.035	0.089	0.056
E4	0.300	0.119	0.119	0.178	0.089	0.035	0.071	0.089	0.056
E5	0.178	0.300	0.119	0.119	0.089	0.071	0.035	0.089	0.056
Aggregated weight	0.225	0.148	0.166	0.181	0.085	0.049	0.056	0.089	-

3.5 TOPSIS ranking of strategies

The five strategies were evaluated against the eight criteria using a nine-point performance scale, where 1 indicates very weak contribution and 9 indicates very strong contribution. The obtained decision matrix is shown in Table 7.

Table 7

TOPSIS decision matrix

Strategy	C1	C2	C3	C4	C5	C6	C7	C8
S1 - Upgrade cold-chain equipment and backup power	9	7	6	9	6	5	6	7
S2 - Deploy digital stock and temperature monitoring	6	9	5	5	8	6	7	6
S3 - Develop regional hubs with route optimization	7	6	8	6	8	5	8	7
S4 - Strengthen last-mile outreach and dedicated transport	5	5	9	5	6	7	7	9
S5 - Improve workforce training and emergency SOPs	5	6	6	5	7	9	9	6

Table 8 presents the weighted normalized matrix. The positive ideal solution is the maximum value in each criterion column and the negative ideal solution is the minimum value in each criterion column.

Table 8.
Weighted normalized decision matrix

Strategy	C1	C2	C3	C4	C5	C6	C7	C8
S1	0.1378	0.0690	0.0640	0.1177	0.0323	0.0166	0.0203	0.0392
S2	0.0919	0.0887	0.0533	0.0654	0.0431	0.0200	0.0237	0.0336
S3	0.1072	0.0591	0.0853	0.0785	0.0431	0.0166	0.0271	0.0392
S4	0.0766	0.0493	0.0960	0.0654	0.0323	0.0233	0.0237	0.0504
S5	0.0766	0.0591	0.0640	0.0654	0.0377	0.0300	0.0304	0.0336

The final TOPSIS distances and closeness coefficients are shown in Table 9. The strategy with the highest closeness coefficient is ranked first. Under the baseline BWM weights, S1, upgrading cold-chain equipment and backup power, obtains the highest closeness coefficient and is therefore the preferred strategy. S3, developing regional hubs with route optimization, ranks second. S2 and S4 have similar closeness coefficients, indicating that digital monitoring and last-mile outreach are both important but slightly less dominant than direct cold-chain and network-structure interventions under the baseline weighting assumptions.

Table 9
TOPSIS results and strategy ranking

Rank	Strategy	D+	D−	Closeness coefficient
1	S1 - Upgrade cold-chain equipment and backup power	0.0440	0.0838	0.6558
2	S3 - Develop regional hubs with route optimization	0.0615	0.0492	0.4446
3	S2 - Deploy digital stock and temperature monitoring	0.0842	0.0439	0.3426
4	S4 - Strengthen last-mile outreach and dedicated transport	0.0908	0.0465	0.3384
5	S5 - Improve workforce training and emergency SOPs	0.0933	0.0228	0.1965

3.6 Sensitivity analysis

A sensitivity analysis was performed to test the stability of the strategy ranking. Four alternative scenarios were examined in addition to the baseline: equal criteria weights, a 30% increase in the weight of equity of last-mile coverage, a 30% increase in the weight of power reliability, and a 30% increase in the weight of transportation accessibility. After each adjustment, weights were normalized to sum to one. Table 10 shows the resulting ranks and closeness coefficients.

Table 10
Sensitivity analysis of TOPSIS rankings

Strategy	Baseline rank / CC	Equal weights rank / CC	Equity +30% rank / CC	Power +30% rank / CC	Transport +30% rank / CC
S1 - Upgrade cold-chain equipment and backup power	1 / 0.656	1 / 0.493	1 / 0.651	1 / 0.682	1 / 0.621
S2 - Deploy digital stock and temperature monitoring	3 / 0.343	5 / 0.372	4 / 0.340	3 / 0.317	4 / 0.325
S3 - Develop regional hubs with route optimization	2 / 0.445	2 / 0.412	2 / 0.443	2 / 0.420	2 / 0.474
S4 - Strengthen last-mile outreach and dedicated transport	4 / 0.338	3 / 0.401	3 / 0.348	4 / 0.316	3 / 0.391
S5 - Improve workforce training and emergency SOPs	5 / 0.196	4 / 0.397	5 / 0.195	5 / 0.181	5 / 0.201

The sensitivity results show that S1 remains the top-ranked strategy in all tested scenarios. This does not imply that other strategies are unimportant. Rather, it suggests that cold-chain equipment and backup power represent a foundational intervention without which digital monitoring, routing improvements, outreach, and training may have limited effect. S3 is also stable, ranking second under the baseline, equal-weight, power-reliability, and transport-focused scenarios. The ranking of S2, S4, and S5 is more sensitive to assumptions about equity and equal weighting, which indicates that these strategies should be interpreted as complementary rather than mutually exclusive.

3.7 Managerial implications

The results suggest three practical implications. First, investment in cold-chain equipment should not be separated from energy reliability. A refrigerator or cold room cannot protect vaccine quality if power interruptions are frequent and backup arrangements are weak. Second, regional distribution design matters. Strengthened hubs and route optimization can reduce delivery time, improve buffer-stock positioning, and support emergency redistribution when shortages or outbreaks occur. Third, technology should be deployed as part of a broader operational system. Digital temperature and stock monitoring can improve visibility, but its value depends on trained staff, reliable maintenance, clear escalation protocols, and coordination across levels of the immunization programme.

4. Conclusions

This paper developed a BWM-TOPSIS framework for prioritizing resilient vaccine distribution strategies in Libya. The proposed model responds to a practical decision problem: health authorities and partners must decide which logistical interventions deserve priority when resources, time, data, and implementation capacity are limited. By combining expert-based criteria weighting with alternative ranking, the framework provides a transparent way to compare interventions across technical, operational, institutional, and equity-related dimensions.

The BWM results indicate that cold-chain equipment and storage capacity, power reliability and backup energy, transportation accessibility, and temperature monitoring are the most influential logistical criteria. This outcome reflects the central role of vaccine quality preservation, service continuity, and safe movement across geographically dispersed areas. The TOPSIS results rank upgrading cold-chain equipment and backup power as the leading strategy, followed by regional distribution hubs with route optimization. Sensitivity analysis confirms the stability of the leading strategy across alternative weighting scenarios.

The study contributes to the literature by adapting an MCDM framework to vaccine logistics in a fragile and infrastructure-constrained setting. It also offers a practical decision-support structure that can be used by national immunization managers, regional health offices, development partners, and logistics planners. The framework is flexible: additional criteria, strategies, cost data, or region-specific performance scores can be incorporated in future applications with recent MCDM models, such as, CODAS [30], AHP [31], MABAC [32]. Moreover, fuzzy sets can be integrated with the proposed model, such as, q-Rung Orthopair Spherical Fuzzy sets [33], Fermatean picture fuzzy [34] or N-fuzzy graph [35] to avoid the hesitancy and uncertainty.

Author Contributions

Conceptualization, I.B. and J.M.; methodology, I.B.; validation, J.M.; formal analysis, I.B.; writing—original draft preparation, I.B.; writing—review and editing, J.M.; supervision, I.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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