Vilnius University Press

Content lists are available at VilniusUniversity Press

Transformations In Business & Economics
2026, Vol. 25 No 1 (67), pp.482-506.

ISSN 1648-4460; E-ISSN 2538-872X
https://doi.org/10.15388/Tibe.2026.25.1.24

A HYBRID MCDM FRAMEWORK FOR OVERCOMING BARRIERS IN THE COVID-19 VACCINE SUPPLY CHAIN

Shahryar Ghorbani
E-mail: shahryar.ghorbani@istinye.edu.tr
ORCID: https://ORCID.org/ 0000-0001-6085-1788
Affiliation: Faculty of Economics, Administrative and Social Sciences, Istinye University, Turkey
ROR: https://ROR.org/03081nz23

Figen Yıldırım
E-mail: figen.yildirim@istinye.edu.tr
ORCID: https://ORCID.org/0000-0002-9247-2245
Affiliation: Faculty of Economics, Administrative and Social Sciences, Istinye University, Turkey
ROR: https://ROR.org/03081nz23

Ali Altug Bicer
E-mail: alialtug.bicer@istinye.edu.tr
ORCID: https://ORCID.org/ 0000-0002-5515-212X
Affiliation: Faculty of Economics, Administrative and Social Sciences, Istinye University, Turkey
ROR: https://ROR.org/03081nz23

Edmundas Kazimieras Zavadskas
E-mail: edmundas.zavadskas@vilniustech.lt
ORCID: https://ORCID.org/0000-0002-3201-949X
Affiliation: Department of Construction Management and Real Estate, Vilnius Gediminas Technical University, Lithuania
ROR: https://ROR.org/02x3e4q36

Jurgita Antucheviciene
E-mail: jurgita.antucheviciene@vilniustech.lt
ORCID: https://ORCID.org/0000-0002-1734-3216
Affiliation: Department of Construction Management and Real Estate, Vilnius Gediminas Technical University, Lithuania
ROR: https://ROR.org/02x3e4q36

Reza Rostamzadeh
E-mail: Reza.Rostamzadeh@iau.ac.ir
ORCID: https://ORCID.org/0000-0002-6161-7173
Affiliation: Big Data Research Center, Islamic Azad University of Urmia, Iran
ROR: https://ROR.org/05km8ys10

Annotation. The COVID-19 pandemic has posed unprecedented challenges globally, with the vaccine supply chain (VSC) serving as a critical lifeline to mitigate the spread of the virus. This paper addresses the significant barriers to the COVID-19 VSC, identifies strategies for overcoming these barriers, and proposes a hybrid multi-criteria decision-making (MCDM) approach for prioritising these strategies. Using the Best-Worst Method (BWM) to determine the weights of barriers and the Weighted Aggregate Sum Product Assessment (WASPAS) method to rank strategies, this study reveals that the most significant barriers include challenges in monitoring and controlling vaccine temperature, maintaining cold chain logistics, and dealing with costs and suboptimal immunisation budgets. The findings suggest that fostering collab-oration, cooperation, and coordination across organisations is the most effective strategy for overcoming the mentioned barriers. This research provides actionable insights for policymakers, healthcare systems, and vac-cine distributors to enhance the efficiency and resilience of the COVID-19 VSC, contributing to global vaccination efforts. The study's implications extend to future pan-demic response planning, offering strategies to build more sustainable and adaptable vaccine supply chains.

Submitted on April 2025. Accepted on November 2025.

Keywords: COVID-19 vaccine supply chain, vaccine distribution challenges, multi-criteria decision-making (MCDM), Best-Worst Method (BWM), Weighted Aggregated Sum Product Assessment (WASPAS), vaccine logistics optimisation, supply chain resilience.

JEL classification: C44, L73, Q55, Q56, R30.

Introduction

The COVID-19 pandemic has put the lives and well-being of billions of people throughout the globe in jeopardy (Ivanov, Dolgui, 2021). The pandemic has resulted in significant changes in the operation of administrative organizations (Narayanamurthy, Tortorella, 2021). A vaccination shortage due to a breakdown of the vaccine supply chain (VSC) would exacerbate the situation in the current environment (Chakraborty, Mali, 2021). A pandemic VSC differs from a standard VSC in how governments buy vaccinations directly from producers, skipping the usual wholesalers and distributors (Abbasi *et al*., 2020). As a result, healthcare specialists and VSC analysts search for excellent policies and tactics to combat the COVID-19 pandemic, including vaccine manufacture and distribution (Abbasi *et al*., 2023). It is critical to analyse the pandemic VSCs and understand the barriers to stop the epidemic's devastation.

COVID-19 vaccinations have been dubbed "the light at the end of the tunnel" to regain normality. Several vaccine manufacturers compete to mass-produce COVID-19 vaccinations (Kim *et al*., 2021). Because of the overall amount necessary by each nation to lower infection rates and prevent lockdowns, the COVID-19 VSC is especially troublesome (Valizadeh *et al*., 2023). To vaccinate 100 percent of people with at least two doses for each person, the total number of vaccine doses necessary is around 2–2.5 times the existing population (16–20 billion doses vs 7 billion population). To contain the latest epidemic, even if 75 percent vaccination is achieved, 12–15 billion vaccine doses would be required globally (Rele, 2021). In 2021 and 2022, many people imagines that the COVID-19 outbreak was coming to an end. It was debilitated, while this virus appeared in different forms, such as viruses of Delta and Omicron. In this situation, the duty of world leaders and the media was to encourage the public to get vaccinated, and the importance of the fact that the COVID 19 virus was not yet finished. The countries of the COVID-19 vaccine manufacturer must consider that different forms of the COVID-19 virus may appear in the future and they need to be responsive within any circumstances (Hu *et al*., 2023). The main supply chain challenges stem from managing significant quantity flows across complicated manufacturer-distributor-healthcare network ties that span multiple countries. Large volumes of material flow through complex networks link manufacturers with transportation providers and medical institutions located across different nations creating major challenges for supply chains (Shiri *et al*., 2024).

The COVID-19 VSC faces challenges that differ from those encountered in previous VSCs related to viruses, such as the SARS epidemic in 2003, the MERS outbreak in 2015, the Ebola outbreaks in 2014 and 2018, and the Zika outbreak in 2016. Despite considerable academic interest in global supply chain literature, supply chain sustainability, and sustainable and resilient supply chain modeling, the specific barriers to the COVID-19 VSC have been insufficiently studied (Cano-Marin *et al*., 2023). To address the gap in existing literature, this study highlights the need to further explore these key barriers. Mismanagement and poor policymaking in the COVID-19 VSC are identified as the primary causes of these challenges, and effective measures to overcome them must be developed. This is especially critical for developing nations, which must recognise, assess, and devise solutions to these obstacles (Sahebi *et al*., 2019).

In this study, a hybrid Multi-Criteria Decision-Making (MCDM) technique is employed to explore the barriers to the COVID-19 VSC. Furthermore, vaccination is crucial for achieving the sustainable development goals (SDGs), as it can save lives and build productive communities through the improvement of healthcare systems (Ratzan *et al.*, 2019). Therefore, the findings of this research hold significant implications for the SDGs.

This research delivers comprehensive understanding of COVID-19 VSC barriers and strategies which can assist pandemic response efforts while helping governments and organisations adapt contingency monitoring and supply chain restructuring plans for future outbreaks. This research also provides explicit VSC-based knowledge about pandemic responses to resolve current pandemic challenges. As a result, the following study's objectives are set:

1) To identify the barriers and overcoming strategies in the COVID-19 VSC;
2) To rank the strategies for overcoming barriers using the BWM-WASPAS approach;
3) To provide practical insights for policymakers to overcome the barriers of VSC.

This research contributes to the existing body of knowledge in various ways. First, it identifies COVID-19 VSC barriers and solutions for overcoming them. Second, it uses the best-worst method to assess barriers and the WASPAS method to assess strategies for overcoming them. Finally, it draws implications of these barriers to help policymakers.

The article is structured as follows. The literature review for COVID-19 VSC and COVID-19 VSCBs is included in Section 2. Section 3 discusses the BWM and WASPAS technique. Section 4 introduces and analyses the suggested hybrid framework's application, whereas Section 5 examines barriers and methods. The last section depicts the study implications, conclusions, and future work prospects.

1. Literature Review

1.1 COVID-19 and Vaccine Supply Chain

The development of COVID-19 vaccines represents a significant scientific breakthrough (Weintraub *et al.*, 2021). In response to the pandemic, nations across the globe have mobilised efforts to introduce licensed vaccines, thereby mitigating the spread and impact of the virus. As of the latest developments, seventeen vaccines have entered Phase II trials, with three (AstraZeneca, Moderna, and Pfizer) having received approval for use in the European Union and the United Kingdom (Warren, Lofstedt, 2021). In an effort to accelerate the global response, the World Health Organisation (WHO) has partnered with international scientists, health organisations, and non-profit entities through the "Access to COVID-19 Tools (ACT)" initiative (Shervani *et al.*, 2020). The successful and equitable distribution of vaccines is critical to minimising the devastating consequences of the pandemic. Therefore, both governmental bodies and academic institutions must prioritise strategies to ensure widespread vaccine availability (Ocampo, Yamagishi, 2020). A key challenge, however, lies in the sustainability of pharmaceutical supply networks as they scale to meet the unprecedented demand generated by this global health crisis (Yu *et al.*, 2020).

National and regional health regulators must authorise vaccines before they progress to the development and fulfilment phases through an interconnected network of supply chain processes that constitute the vaccine supply chain (VSC). The availability of the vaccine primarily depends on overcoming supply chain obstacles in both the development and de-livery stages. The development of new vaccines, alongside studies on human effects, should receive equal emphasis as VSC solutions that enhance vaccination outcomes (Lee, Haidari, 2017). According to the WHO, 42 COVID-19 vaccines are currently in clinical trials, with 151 potential vaccines undergoing preclinical testing. Approximately 280,000 participants from 34 countries are expected to take part in these vaccination studies. With the lifting of COVID-19-related restrictions, rapid vaccine distribution is seen as a game-changer, enabling the economy to recover more swiftly (Goodwin, 2021).

The COVID-19 vaccine analysis became prominent throughout all scientific publications since the beginning of the epidemic (Dey *et al*., 2024). The work developed criteria to evaluate COVID-19 vaccination procedures. According to this study the novel paradigm shows potential for assisting with scenario development and trade-off analysis between different vaccination methods. The vaccine distribution model in the downstream supply chain was developed with variable assignments and distribution routes. A study examined how vaccine manufacturers act to deter fake vaccines and apply worldwide tracking protocols into their supply networks. The development of vaccines within pandemic periods is examined along with identified shortcomings and potential improvements for future pan-demic responses. These COVID-19 vaccine studies made commendable contributions but neglected to examine COVID-19 VSC's problems. By employing MCDM analysis this study studies every possible obstacle affecting the COVID-19 VSC system. This combination with multi-faceted decision analysis systems can more quickly and efficiently cope with complex decision-making processes.

1.2 Recognition of COVID-19 VSC Barriers

To gather data for this investigation, a multi-stage survey was used. The first step of the survey consisted of an actuality consultation with specialists to better understand the COVID-19 VSC barriers. A list of eight specialists (*Table 1*) was selected following participant evaluation of VSC and healthcare procedures. *Table 1* displays experts from various VSC regions including vaccine producers alongside vaccine purchasers and distributors. Specialists from knowledge-based organisations and government advisors demonstrate superior involvement in comprehending the COVID-19 VSC barrier.

Table 1. List of Participants in the Interview

Experts	Position	Experience	Organisation
E1	SC manager	10	Pharmaceutical industry
E2	Professor, Industries sector	15	University
E3	Professor, Vaccine sector	11	Medical sciences university
E4	Senior management	15	Vaccine industry
E5	Managing Director	10	Supplier
E6	Professor of SC	18	Medical sciences university
E7	Quality management	10	Vaccine industry
E8	Senior Professor	16	Pharmaceutical industry

Source: created by the authors.

The literature review found twelve barriers. Accordingly, a barrier was included or eliminated if at least six of the eight experts (or 75% of the total) agreed or disagreed regarding its relationship to VSC. Four barriers are counted in the list of 12 barriers, while two are eliminated, namely "Immunisation programme delivery methodologies" and "Topographical limits". After that, 20 COVID-19 VSC barriers are chosen. *Appendix 1* lists the obstacles and specifies whether they are based on research or expert opinion. Manufacturing barriers (B1), behavioural barriers (B2), last-mile delivery barriers (B3), cold chain barriers (B4), and organisational barriers (B5) are the five types of listed barriers. These categories are presented in *Appendix*

1. It is crucial to mention that the obstacles listed below do not represent all of the COVID-19 VSC's barriers.

1.3 VSCBs Overcoming Strategies

More specifically, systematic investigations that have recognised and prioritised barriers for advising leaders to determine the considerably intense barriers requiring immediate attention versus those that can be postponed and recognised and prioritised some overcoming pro-cesses to manage these barriers stay scarce (Kargar *et al*., 2024). As a result, this research is justified and prompted by the absence of studies that fully identify the challenges to COVID-19 VSC setup in developing and developed nations and solutions to overcome such barriers. Vaccine production companies contribute substantially to those countries' health and the developing worldwide sustainability challenge in COVID-19 prevention. One strategy to advance the sustainable development agenda in COVID-19 VSC is to focus on this research by examining the challenges and solutions for controlling the barriers to COVID-19 VSC (Ivanov, Dolgui, 2021). As a result, this research uses a multi-criteria decision-making process to develop and analyse a complete framework of barriers and over-coming strategies for COVID-19 VSC, which is presented in *Table 3*.

Table 3. COVID-19 VSCBs Overcoming Strategies

Strategies	Description
Economic and incen-tives-based strategy (ST1)	Foreign societies often project an unfavourable image of the country (negative advertising, political and economic sanctions). Improving the environment for foreign investment and assisting the local private sector in developing the country's VSC infrastructure.
Sustainable profi-ciencies and skill de-velopment strategy (ST2)	This strategy intends to create an atmosphere that encourages workers and doctors to build green and sustainable capabilities, such as skills and know-how, to develop sustainable technologies and ideas to reduce environmental damage.
Long-term strategic planning (ST3)	Long-term evaluations that aid in determining overall strategy orientations for supply chain management are addressed in strategic planning. Great choices are part of strategic planning.
Research and devel-opment strategy (ST4)	This plan intends to help vaccine producers create and strengthen research fa-cilities to develop and improve service.
Collaboration, coop-eration, and coordi-nation among organi-sations (ST5)	To meet the demands of the COVID-19 vaccination chain, collaboration, coop-eration, and integration among players are required.
Marketing and pro-motion strategy (ST6)	Prioritising investment attraction among other policies for attracting foreign re-sources, identifying barriers and points of incentive policies to attract medical and health funders, identifying domestic capabilities in the vaccine field, build-ing trust in quality services in the country, and directing the need to domestic resources.
Networking strategy (ST7)	This approach aims to develop collaborative skills and competencies inside and external organisations and institutions. Collaboration might take the form of equipment technology sharing, collaborative employee and physician train-ing.

Source: created by the authors.

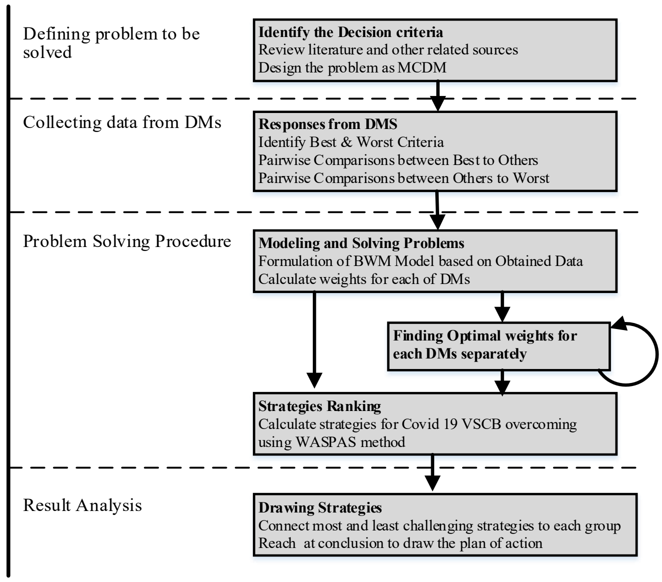
1.4 Research Highlights

Various obstacles impede the system development of COVID-19 VSC's. Healthcare workers operating in COVID-19 VSCs must address the identified system barriers. The present literature review failed to uncover any non-studies about barriers in the COVID-19 vaccine business domain. Research has not been performed to determine which COVID-19 VSC barriers are most relevant. Available research does not provide methods for addressing these obstacles (Bhattacharya *et al*., 2024; Mehra *et al*., 2024). This research begins by identifying obstacles facing COVID-19 VSCs in a designated setting before presenting a strategy collection for handling those obstacles. It also assesses barrier priority levels as well as strategies for their overcome. According to the literature, no research does not use BWM and WASPAS (Zavadskas *et al*., 2012) for VSCBs problem analysis, and based on the following reasons the integrated methodology was selected:

- Relatively new MCDM methods, such as the BWM, can cope with barriers. BWM uses subjective data that characterises humans' judgments and behaviours during the choosing process. Being different from AHP, the BWM method allows a consistent pairwise comparison of evaluation criteria to be made (Corrente *et al*., 2024; Ecer *et al*., 2024; Gao *et al*., 2024; Shahrabi-Farahani *et al*., 2024).
- WASPAS can work with linguistic variables. Should there be some conflicting criteria in the decision problem, this method can be very useful. Thus, the proposed integrated methodology can be closer to the actual decision-making problems, such as VSCBs assessment (Arslan, Cebi, 2024; Chakraborty *et al*., 2025; Singh, 2024).

2. Methodology

The present research was carried out in three phases. The research team initially interviewed healthcare specialists alongside VSC experts who subsequently refined and contributed research-obtained barriers.



Source: created by the authors.

Figure 1. **Framework of Research for Evaluating COVID-19 VSCB**

A questionnaire which contained the identified barriers was provided to experts who then responded using linguistic rating scales during the second phase. BWM-WASPAS performs final stage data analysis. A pictorial illustration in *Figure 1* shows the methodical development steps for this project.

2.1 Best-Worst Method

When using the Best-Worst Method (BWM) as a comparison-based MCDM method, researchers compared the best criterion to every other criterion, and all other criteria was compared to the worst criterion. Through linear optimisation, the system developed a basic model for identifying the optimal ratio and weights based on the comparison system inputs (Rezaei, 2016). The BWM method found applications across different research domains, such as logistics performance optimisation (Gupta, Barua, 2018), sustainable oil supply chain management (Ahmadi *et al.*, 2017), and medical tourism development (Gupta, Barua, 2016), along with the optimal search model, web service selection, and research and development investment opportunities (Rezaei *et al.*, 2016). The processes of BWM to determine the criterion's weight are described as follows (Mohammadi, Rezaei, 2019):

Step 1: Decision-makers determine the set of decision criteria $\{c_1, c_2, \dots, c_n\}$.

Step 2: Decision on the best and worst criteria to utilise in the decision-making environment. In this stage, based on their preferences, the decision-makers choose the best and worst criteria from the criteria given in Step 1. The most significant criteria are represented by the best criterion, while the worst represents the least important criterion.

Step 3: Determination of the preference of the best criterion over all the other criteria. This value is represented by a number between 1 and 9 (see *Table 4*). $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$ would be the resultant Best-to-Other's vector, where a B_j implies that criteria B (the best criterion) is preferred above criterion j and $a_{BB} = 1$.

Table 4. Linguistic Terms and Corresponding Value

Linguistic terms	Abbreviation	Values
Equally important	EI	1
Very weakly important	VWI	2
Weakly important	WI	3
Less important	LI	4
Fairly important	PI	5
Really important	RI	6
Very important	VI	7
Very highly important	VVI	8
Absolutely important	AI	9

Source: created by the authors.

Step 4: Determination of the preference of each of the other criteria over the worst criterion. In this situation, a number between 1 and 9 is also selected, where $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$ would be the Others-to-Worst vector. Here, a_{jW} denotes the preference of the criterion j over the worst criterion W, and a_{WW} denotes the preference of the criterion j over the worst criterion W.

Determination of the best weights $w_1^*, w_2^*, \dots, w_n^*$. The best weights for the criterion will be determined by solving Equation (1). To determine the optimal weights of the criteria, the maximum absolute differences $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ are calculated. Referring to all $j = 1,2, \dots, n,$ it should be minimised:

$$\min \ \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jw} \right| \right\} \tag{1}$$

subject to

$\sum_j w_j = 1, \quad w_j \geq 0$ for all j.

The optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and the optimal value of ξ^* are found by solving this problem. The consistency ratio of the comparison system is defined as ξ^* in the linear model. It indicates that the closer ξ^* is to 0, the more consistent the comparison system provided by the decision-makers.

2.2 Weighted Aggregated Sum Product Assessment

The complex evaluation of real-world scenarios using a high number of criteria becomes simpler with the implementation of effective multicriteria support systems. Different re-search teams have built multiple criteria decision-making (MCDM) systems using various factors as their foundation (Sahoo, Goswami, 2023). The precision level of these samples represents an essential criterion for selecting appropriate multi-criteria decision systems. According to scientific reports, the combination of multiple models leads to enhanced pre-dictive capacity (Yang, 2025). The WSM (weighted sum model) and WPM (weighted product model) produce multi-attribute decision results which have established an out-standing level of precision. The study analysed the way compound samples aligned with truth. Research shows that hybrid samples maintain substantially higher accuracy levels when compared to independent samples preceding their combination. The weighted ag-gregated sum product assessment (WASPAS) sample represents a method of choice which exhibits efficiency in solving complex decision-making problems and creates accurate results (Zavadskas *et al*., 2012).

Table 5. Evaluation Scale

Linguistic variable	Value
Extremely unimportant	0.1
Not very important	0.3
Not important	0.5
Fair	0.7
Important	0.9
Very important	1

Source: created by the authors.

One of the most well-known decision-making approaches for multicriteria issues is the weighted sum model. Here, m choices (alternatives) and n decision criteria constitute a multicriteria issue. The relative relevance of the criteria is represented by w_j, and the performance value of option i in terms of criterion j is represented by x_{ij}. A decision matrix is created using expert views, as shown in *Table 5*:

$$\hat{X}_{ij} = \begin{bmatrix} \hat{x}_{11} & \hat{x}_{12} & \cdots & \hat{x}_{1n} \\ \hat{x}_{21} & \hat{x}_{22} & \vdots & \hat{x}_{2n} \\ \cdots & \cdots & & \cdots \\ \hat{x}_{m1} & \hat{x}_{m2} & \cdots & \hat{x}_{mn} \end{bmatrix}. \quad (2)$$

In Equation (3), the relative relevance of option i is represented by $Q_i^{(1)}$, where $\bar{x}_{ij}$ is the normalised value of the j^{th} criterion of alternative i:

$$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij} \times w_j. \quad (3)$$

The relative significance of option *I* is provided as $Q_i^{(2)}$ in the weighted product model, which is shown in Equation (4):

$$Q_i^{(2)} = \max \prod_{j=1}^{n} \left(\bar{x}_{ij}\right)^{w_j}. \tag{4}$$

As shown in Equation (5), a mix of criteria was used to evaluate the ultimate relevance of each option, with an equal amount of WSM and WPM used for the final assessment of alternatives:

$$Q_i = 0.5Q_i^{(1)} + 0.5Q_i^{(2)},$$
$$Q_i = \lambda \sum_{j=1}^{n} \bar{x}_{ij} w_i + (1-\lambda) \prod_{j=1}^{n} \left(\bar{x}_{ij}\right)^{w_j}, \quad \lambda = 0, \dots, 1. \tag{5}$$

In this study, the parameter λ is considered a continuous variable within the interval [0, 1], i.e., $\lambda \in [0,1]$. The interval was not discretised. Instead, as shown in Equation (6), the optimal value of λ was determined based on the variance contributions of the additive **(**WSM**)** and multiplicative **(**WPM**)** components. This variance-based formulation enables a balanced aggregation of both models, enhancing the robustness and accuracy of the final decision scores in the WASPAS method. By extending the following equation, the optimum values of λ may be calculated:

$$\lambda = \frac{\delta^2(Q_i^{(2)})}{\delta^2\left(Q_i^{(1)}\right) + \delta^2(Q_i^{(2)})}, \tag{6}$$

where $\delta^2\left(Q_i^{(1)}\right)$ and $\delta^2(Q_i^{(2)})$ must be calculated from Equations (7) and (8):

$$\delta^2\left(Q_i^{(1)}\right) = \sum_{j=1}^{n} \bar{x}_{ij} w_j^2 \delta^2(\bar{x}_{ij}), \tag{7}$$

$$\delta^2\left(Q_i^{(2)}\right) = \sum_{j=1}^{n} \left[\frac{\prod_{j=1}^{n}\left(\bar{x}_{ij}\right)^{w_j} * w_{ij}}{\left(\bar{x}_{ij}\right)^{w_j}\left(\bar{x}_{ij}\right)^{(1-w_j)}}\right]^2 \delta^2\left(\bar{x}_{ij}\right). \tag{8}$$

The estimation of the variance of the primary normalised values of the criteria can also be calculated by the Equation (9):

$$\delta^2\left(\bar{x}_{ij}\right) = \left(0.05\bar{x}_{ij}\right)^2. \tag{9}$$

The suggested framework may be used to help stakeholders recognise the relative relevance of COVID-19 VSC barriers and prioritise several possible solutions for overcoming VSCBs, promoting effective and efficient COVID-19 vaccine chain processes, and improving COVID-19 VSC actions and procedures. The WASPAS is used to rank the solutions to control COVID-19 VSC barriers, while the BWM is used to determine the weights of COVID-19 VSC barriers and assess their relative relevance. Founded on a literature analysis and expert brainstorming sessions, this research presents 21 COVID-19 VSC hurdles and seven solutions to overcome them (see *Table 3*). The structural conclusion order for this research has three levels, which indicate the ranking of options to control COVID-19 VSC hurdles. At the beginning level, COVID-19 VSC barriers obstruct effective COVID-19 VSC execution at the middle level and solutions to control COVID-19 VSC barriers at the final level.

3. Results

3.1 BWM Results

The suggested best-worst technique is used to build a framework to assess the COVID-19 vaccine supply chain obstacles criteria in this section. It contains the steps of determining linguistic phrases, identifying obstacles for assessing the COVID-19 vaccine supply chain, determining necessary weights for assessment barriers, calculating and ranking the barriers. The estimation barriers are divided into four dimensions and 21 sub-barriers. The weights of five key obstacles will be computed first (for example, calculations related to three experts are given). *Table 6* and *Table 7* show the Best-to-Others and Worst-to-Others vectors from three assessors.

Table 6. Different Assessors' Choices for the Best Criteria Over All the Significant Barriers

		$\boldsymbol{T}$	$\boldsymbol{SA}$	$\boldsymbol{OOS}$	$\boldsymbol{M}$
e_1, $w_1^e = 0.32$	$Best\ criterion$: $\boldsymbol{T}$	1	5	8	4
e_2, $w_2^e = 0.34$	$Best\ criterion$: $\boldsymbol{M}$	4	8	6	1
e_3, $w_3^e = 0.34$	$Best\ criterion$: $\boldsymbol{T}$	1	5	8	3

Source: created by the authors.

Table 7. Different Assessors' Choices for the Worst Criteria Overall Key Barriers

		$\boldsymbol{Worst\ criterion}$:	$\boldsymbol{OOS}$
e_1, $w_1^e = 0.32$	$\boldsymbol{T}$	8	
	$\boldsymbol{SA}$	4	
	$\boldsymbol{OOS}$	1	
	$\boldsymbol{M}$	5	
		$Worst\ criterion$:	$\boldsymbol{SA}$
e_2, $w_2^e = 0.34$	$\boldsymbol{T}$	6	
	$\boldsymbol{SA}$	1	
	$\boldsymbol{OOS}$	3	
	$\boldsymbol{M}$	8	
		$Worst\ criterion$:	$\boldsymbol{OOS}$
e_3, $w_3^e = 0.34$	$\boldsymbol{T}$	8	
	$\boldsymbol{SA}$	4	
	$\boldsymbol{OOS}$	1	
	$\boldsymbol{M}$	6	

Source: created by the authors.

$$\min \xi \quad \text{subject to} \tag{10}$$

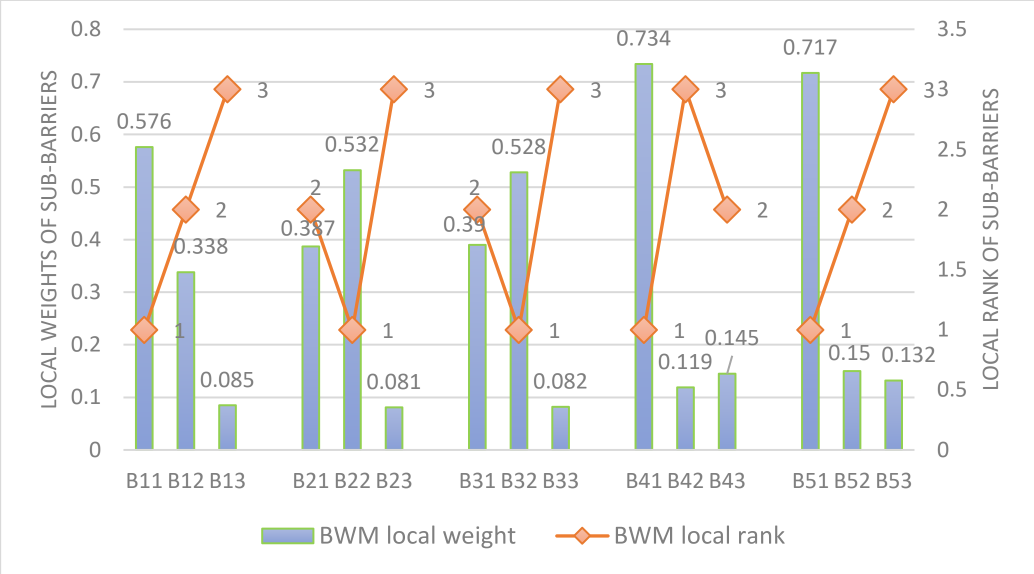
$$\begin{cases} \left|\frac{B_1}{B_2}-5\right| \le \xi, \quad \left|\frac{B_1}{B_3}-8\right| \le \xi, \quad \left|\frac{B_1}{B_4}-4\right| \le \xi, \\ \left|\frac{B_1}{B_5}-7\right| \le \xi, \quad \left|\frac{B_2}{B_3}-4\right| \le \xi, \quad \left|\frac{B_4}{B_3}-3\right| \le \xi, \\ \left|\frac{B_5}{B_3}-3\right| \le \xi, \\ \sum_{j=1}^{6} w_j = 1, \\ w_j \ge 0, \quad j = 1,2,\ldots,6. \end{cases}$$

Solving the model (8) as $w_{e_1}^{1*} = 0.410$, $w_{e_1}^{2*} = 0.082$, $w_{e_1}^{3*} = 0.089$, $w_{e_1}^{4*} = 0.308$,this yields the ideal weights of the five main barriers according to evaluator one view. Similarly, the weights of the four main barriers were estimated according to all evaluators. Then the average of the acquired weights was computed to get the final ideal weights of the four major barriers. As illustrated in the centre of *Table 8*, the preferences of sub-barriers for major criteria may be created, and the corresponding local weights of sub-barriers for each major criterion can be derived. The global weights of all 21 sub-barriers may be determined; their rankings are shown on the right side of *Table 8*. As a result, the consistency ratio may be estimated as 0.054, which is near zero, indicating excellent consistency.

Table 8. The Weights and Ranking of all the 15 VCSBs

$Criteria$	T $w_1^* = 0.410$	SA $w_2^* = 0.102$	OOS $w_3^* = 0.089$	M $w_4^* = 0.308$	$Global$ $Weight$	$Ranking$
$Sub-criteria$						
$T1$	0.466				0.192	2
$T2$	0.288				0.119	4
$T3$	0.137				0.056	6
$T4$	0.108				0.028	11
$SA1$		0.122			0.012	14
$SA2$		0.352			0.038	7
$SA3$		0.282			0.030	10
$SA4$		0.165			0.016	13
$SA5$		0.072			0.003	20
$OOS1$			0. 094		0.008	16
$OOS2$			0. 112		0.010	15
$OOS3$			0.624		0.058	5
$OOS4$			0.082		0.007	17
$OOS5$			0.049		0.004	19
$OOS6$			0.057		0.006	18
$M1$				0. 99	0.032	9
$M2$				0. 101	0.035	8
$M3$				0.411	0.132	1
$M4$				0.391	0.121	3
$M5$				0.092	0.023	12

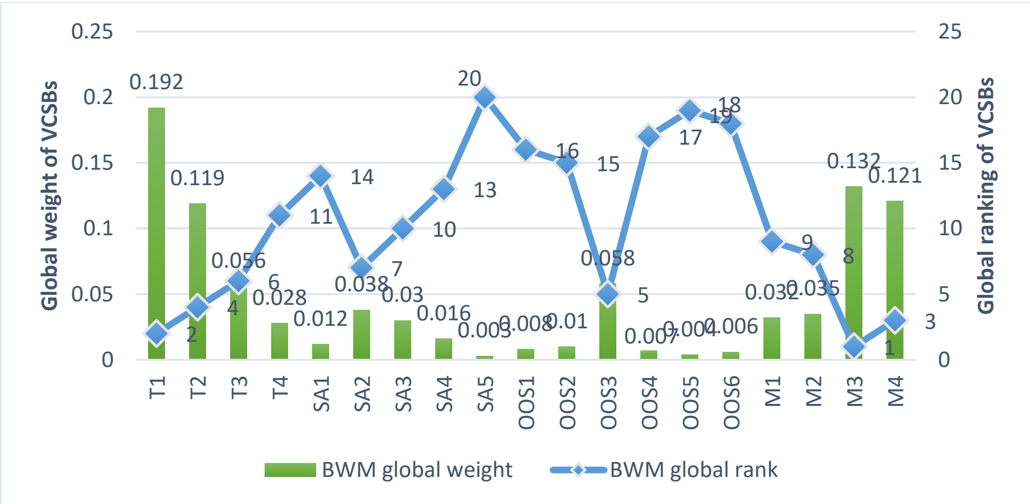
Source: created by the authors.



Source: created by the authors.

Figure 2. **Local Weight and Local Ranking of VSCBs**

After obtaining local weights for barriers and sub-barriers based on each expert's opinion, final local weights and local ranks are calculated by averaging the weights (as graphically shown in *Figure 2*). Also, the graphical representation of VSC barriers BWM global weight (GW) and global ranking (GR) is shown in *Figure 3*.



Source: created by the authors.

Figure 3. **Global Weight (GW) and Global Ranking (GR) of VSCBs**

In *Figure 3*, the ranking of the 15 barriers, with $M3$: difficulties in monitoring and controlling vaccine temperature, $T1$: maintaining cold chain logistics, and $M3$: costs and suboptimal immunisation budgets top three, are presented.

3.2 WASPAS Results

Following the derivation of the COVID-19 VSCBs' weights from the BWM, the WSPAS is utilised to rank the strategies that pass the COVID-19 VSCB, yielding a total of seven strategies to overcome the COVID-19 VSCB. They are labeled $S_1, S_2, \ldots, S_7$, and WSPAS will be used to assess them. The expert panel assigned a score to each option using the grading scale presented in *Table 5* and developed a WASPAS decision matrix in *Table 9*. Then Eq. (3) is used to produce the WASPAS decision matrix's normalised values (see *Table 10*).

The terms X_{ij} establish a WASPAS normalised weight decision matrix for summation; they are constructed using Eq. (4) (see *Table 11*). Multi-kernel weighted decision matrix WASPAS based on terms X_{ij} is computed using Eq. (5). *Table 12* presents 10 of them. The defuzzification of the dimming efficiency measure was done using the center technique and Eq. (5). Lastly, the weighted collection of totalities and multipliers is calculated using Eq. (6).

Based on their Q_i value, VSCB were ranked. The WSPAS findings are shown in *Table 13*. In addition, the Eq. (3) yields the nearest fuzzy weight $(\widehat{w}_j)$ of the COVID-19 VSCBs. In addition, the WASPAS method uses the BWM technique to rank ways to control COVID-19 VSCB; the results are shown in *Table 13*. This table compares the ratings of techniques to overcome COVID-19 VSCB by calculating the relative weight, $(\widehat{w}_j)$, and the relative weight, indexed by j, of every COVID-19 VSCB.

Table 9. WASPAS Decision Matrix

CVSCBs	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*
T1	0.367	0.367	0.700	0.433	0.433	0.767	0.433
T2	0.733	0.500	0.567	0.500	0.867	0.567	0.500
T3	0.433	0.500	0.367	0.633	0.500	0.433	0.567
T4	0.700	0.733	0.667	0.567	0.567	0.633	0.600
SA1	0.567	0.433	0.767	0.800	0.433	0.633	0.500
SA2	0.567	0.600	0.633	0.633	0.567	0.433	0.567
SA3	0.733	0.567	0.500	0.767	0.633	0.500	0.567
…..	…..	…..	…..	…..	…..	…..	…..
… ..	… ..	… ..	… ..	… ..	… ..	… ..	… ..
OOS5	0.500	0.700	0.367	0.633	0.800	0.500	0.500
OOS6	0.700	0.800	0.500	0.567	0.800	0.500	0.700
M1	0.500	0.567	0.700	0.367	0.500	0.800	0.433
M2	0.667	0.567	0.500	0.767	0.867	0.633	0.500
M3	0.633	0.433	0.567	0.567	0.700	0.567	0.433
M4	0.567	0.567	0.500	0.300	0.733	0.767	0.567
M5	0.433	0.500	0.500	0.367	0.700	0.433	0.500

Source: created by the authors.

Table 10. WASPAS Normalised Decision-Making Matrix

CVSCBs	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*
T1	5.102	5.102	2.673	4.317	4.317	2.440	4.317
T2	2.806	4.115	3.631	4.115	2.374	3.631	4.115
T3	4.276	3.706	5.053	2.926	3.706	4.276	3.270
T4	3.019	2.882	3.170	3.730	3.730	3.337	3.522
SA1	3.588	4.692	2.652	2.541	4.692	3.210	4.066
SA2	3.529	3.333	3.158	3.158	3.529	4.615	3.529
SA3	2.817	3.645	4.131	2.694	3.261	4.131	3.645
…..	…..	…..	…..	…..	…..	…..	…..
… ..	… ..	… ..	… ..	… ..	… ..	… ..	… ..
OOS5	3.053	2.671	4.274	3.771	2.671	4.274	3.053
OOS6	3.933	3.470	2.809	5.363	3.933	2.458	4.538
M1	3.182	3.744	4.243	2.767	2.448	3.349	4.243
M2	3.118	4.557	3.485	3.485	2.821	3.485	4.557
M3	3.529	3.529	4.000	6.667	2.727	2.609	3.529
M4	4.276	3.706	3.706	5.053	2.647	4.276	3.706

Source: created by the authors.

Table 11. WSM Matrix

CVSCBs	$S1$	$S2$	$S3$	$S4$	$S5$	$S6$	$S7$
$T1$	0.903	0.903	0.473	0.764	0.764	0.432	0.764
$T2$	0.292	0.428	0.378	0.428	0.247	0.378	0.428
$T3$	0.111	0.096	0.131	0.076	0.096	0.111	0.085
$T4$	0.957	0.914	1.005	1.182	1.182	1.058	1.117
$SA1$	0.158	0.206	0.117	0.112	0.206	0.141	0.179
$SA2$	0.021	0.020	0.019	0.019	0.021	0.028	0.021
$SA3$	0.096	0.124	0.140	0.092	0.111	0.140	0.124
…..	…..	…..	…..	…..	…..	…..	…..
… ..	… ..	… ..	… ..	… ..	… ..	… ..	… ..
$OOS5$	0.919	0.804	1.286	1.135	0.804	1.286	0.919
$OOS6$	0.193	0.170	0.138	0.263	0.193	0.120	0.222
$M1$	0.188	0.221	0.250	0.163	0.144	0.198	0.250
$M2$	0.243	0.355	0.272	0.272	0.220	0.272	0.355
$M3$	0.056	0.056	0.064	0.107	0.044	0.042	0.056
$M4$	0.060	0.052	0.052	0.071	0.037	0.060	0.052

Source: created by the authors.

Table 12. WPM Matrix

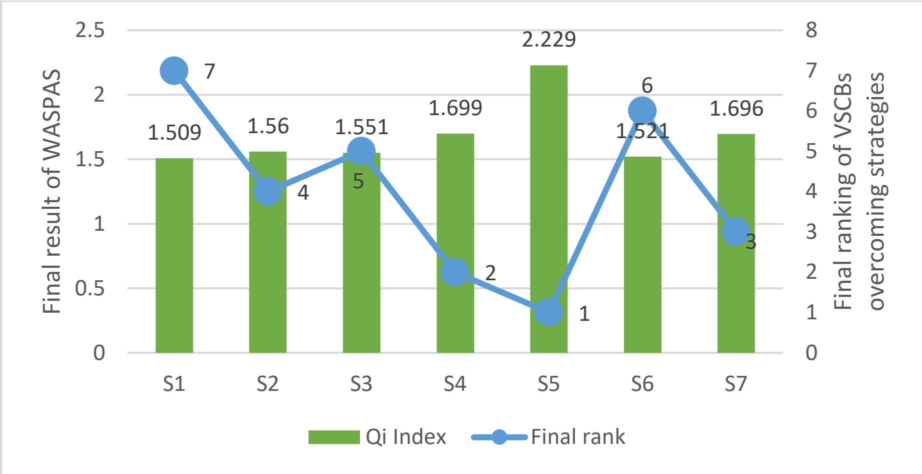
CVSCBs	$S1$	$S2$	$S3$	$S4$	$S5$	$S6$	$S7$
$T1$	1.334	1.334	1.190	1.295	1.295	1.171	1.295
$T2$	1.113	1.158	1.144	1.158	1.094	1.144	1.158
$T3$	1.039	1.035	1.043	1.028	1.035	1.039	1.031
$T4$	1.419	1.399	1.442	1.518	1.518	1.465	1.491
$SA1$	1.058	1.070	1.044	1.042	1.070	1.053	1.064
$SA2$	1.008	1.007	1.007	1.007	1.008	1.009	1.008
$SA3$	1.036	1.045	1.049	1.034	1.041	1.049	1.045
…..	…..	…..	…..	…..	…..	…..	…..
… ..	… ..	… ..	… ..	… ..	… ..	… ..	… ..
$OOS5$	1.399	1.344	1.548	1.491	1.344	1.548	1.399
$OOS6$	1.069	1.063	1.052	1.086	1.069	1.045	1.077
$M1$	1.071	1.081	1.089	1.062	1.054	1.074	1.089
$M2$	1.093	1.126	1.102	1.102	1.084	1.102	1.126
$M3$	1.020	1.020	1.022	1.031	1.016	1.015	1.020
$M4$	1.021	1.019	1.019	1.023	1.014	1.021	1.019

Source: created by the authors.

Table 13. WPM Matrix

Strategies	Aggregate summation value	Aggregate multiplication value	Qi	Ranking
$S1$	1.669	1.354	1.509	7
$S2$	1.730	1.395	1.560	4
$S3$	1.700	1.407	1.551	5
$S4$	1.845	1.558	1.699	2
$S5$	3.212	1.279	2.229	1
$S6$	1.669	1.378	1.521	6
$S7$	1.842	1.555	1.696	3

Source: created by the authors.



Source: created by the authors.

Figure 4. **Final Ranking Results of BWM-WASPAS**

4. Discussion

4.1 Discussion on the Barriers Prioritisation Results

Data from Table 8 indicates that difficulties in monitoring and controlling vaccine temperature (M3) emerge as the primary challenge, according to the survey results. Specialist evaluations indicate that "Difficulties in monitoring and controlling vaccine temperature (M3)" produce the highest influence on "Inadequate planning and scheduling (OOS2)", "Unavailability of volunteers for vaccine trials (SA5)", "Increase in acquisition lead time (OOS4)", and "Improper coordination with local administration (SA3)". This direct issue affects two other barriers, including "Supply chain issues (OOS1)" and "Inadequate storage systems (M2)". While the Vaccine Supply Chain (VSC) literature does not identify a specific vaccine monitoring authority, studies emphasise the importance of robust temperature monitoring systems. For instance, research by Kartoğlu *et al*. (2010) highlights the significance of improving temperature monitoring in the vaccine cold chain at peripheral levels. Furthermore, Chojnacky *et al*. (2011) discuss methods for accurate cold-chain temperature monitoring using digital data-logger thermometers. These studies underscore the critical role of effective temperature monitoring in maintaining vaccine efficacy and ensuring the integrity of the supply chain.

The second identified barrier is "Maintaining cold chain logistics (T1)". It has a significant impact on the "Deficiency of Optimum number of cold chain vehicles (M1)", an indirect impact on "Cost (OOS2)" and "Limited vaccine production organisation (OOS5)", according to the experts. This discovery states that all authorised COVID-19 vaccines must be kept in cold conditions throughout manufacture, shipping, and distribution to healthcare institutions. Similarly, Chen *et al*. (2015) claim that effective immunisation programmes require the development of adequate storage facilities (e.g., refrigerators, freezers, and cold rooms) as well as trucks with temperature monitoring systems. Burgos *et al*. (2021) further emphasise the need to monitor vaccine temperature throughout the VSC. As a result, future research in the VSC should focus on transportation and cold chain issues (Dai *et al*., 2021).

Third in order of significance stands "Costs and Suboptimal immunisation budgets (M4)". The published VSC literature continues to validate the critical importance of this barrier. The "Production failure at an early stage (T2)" is the fourth-highest barrier. "Costs and Suboptimal immunisation budgets (M4)", "Increase in acquisition lead time (OOS4)", and "Production capacity (T4)" are some of the obstacles. According to literature, there are only six vaccine production firms with a total capacity of around 10 billion doses: "AstraZeneca", "Novavax", "Johnson & Johnson", "Moderna", "Pfizer", and "BioNTech". This barrier is especially significant since Kim *et al*. (2021) estimate that 10–11 billion vaccination doses are needed to block viral transmission effectively. Based on the report by Bozorgmehr *et al*. (2021), Pfizer-BioNTech, Moderna, and AstraZeneca are already experiencing production delays. The results of this study explain these manufacturing delays, since it was discovered that a "Production failure at an early stage (T2)" influences the "Production capacity (T4)".

Finally, "inadequate planning and scheduling (OOS3)" is the COVID-19 VSC's next major roadblock. Based on the report of the specialists, this barrier has a significant impact on "Improper coordination with local administration (SA3)", "Complexity in SC regulatory life cycle management (OOS6)", and "Unavailability of volunteers for vaccine trials (SA5)". Governments often purchase pandemic vaccinations and distribute them to local healthcare providers to vaccinate the country's whole population. Expert interviews revealed that teamwork between the local and state levels is critical for a successful immunisation programme. For example, Henao-Restrepo *et al*. (2015) claim that proper coordination of local and state institutions for the Ebola outbreak resulted in a speedier vaccination procedure. The communication between the municipal and state administrations, on the other hand, has been inconsistent in several instances. For example, based on the article by Freed (2021), it is unclear if and how people would be told about the vaccine's second dosage. Furthermore, Lee and Haidari (2017) show that vaccine shortages and predictability of vaccination demand might become difficult without sufficient coordination between the state and local levels, obstructing efficient and timely vaccine delivery. As a result, future studies might look at measures to guarantee VSC's efficacy and efficiency by establishing suitable coordination between local and state-level institutions (Shamsi, Torabi, 2018). The issues revealed in this study are important, as seen in the preceding paragraphs. As a result, these issues require the greatest attention from academics worldwide to detect and recommend effective solutions to these problems as quickly as feasible.

4.2 Discussion on the VCSBs Overcoming Strategies Ranking Results

The disparity in the overall score weight of every procedure with barriers suggests that one technique is not adequate to control these barriers, as shown by the examination of ways to beat obstacles to COVID-19 VSC (second phase of the investigation) (see *Table 11*). The following is a ranking of techniques to control COVID-19 VSCB based on the fuzzy WASPAS results: $S_5 > S_4 > S_7 > S_2 > S_3 > S_6 > S_1$. The results are also illustrated in *Figure 3*. WSPAS findings reveal that collaboration, cooperation, and coordination across organisations (ST5) are best (first) for dealing with them. ST4 (Research and Development) is placed second to control COVID-19 VSCB. The third-highest technique to overcome the barriers is the networking process (ST7). The fourth highest ranked option for overcoming hurdles is the Sustainable Proficiencies and Skill Development Strategy (ST2). $B_{11}, B_{13}, B_{32}, B_{42}, B_{51}, B_{52}$, and B_{53} are examples of impediments that may be addressed by collaboration, cooperation, and coordination across companies (ST5).

4.3 Comparative Study

This article discusses how to overcome vaccine supply chain disruptions during the global COVID-19 pandemic, using a selected country as an example. Although the development of vaccines for COVID-19 has undoubtedly been a significant challenge and a global problem, the focus of the medical and other scientific communities has led to positive results. However, it should be noted that specific barriers may increase the difficulty to achieve universal/significant uptake of vaccines. The paper highlights a scientific problem that calls for the exploration of barriers in the COVID-19 vaccine supply chain and identification of strategies to overcome these barriers, focusing on real-time decision-making, component support, and changing and complex business conditions. This study uses the Weighted Aggregate Sum Product Assessment (WASPAS) method to rank the proposed strategies. Besides, to determine the weight of barriers the best-worst method was used for ranking the overcoming strategies.

This paper identifies fifteen barriers and reveals that "Difficulties in monitoring and controlling vaccine temperature" (M3), "Maintaining cold chain logistics" (T1), and "Costs and Suboptimal immunization budgets" (M4), are the most challenging barriers. WASPAS findings reveal that "collaboration, cooperation, and coordination across organizations" is the best strategy for overcoming the barriers. "Research and development strategy" is placed second to control the COVID-19 VSC barriers.

The proposed methodological approach in this study is novel and distinct from recent works in the field. Unlike previous studies that have primarily focused on qualitative analyses or single-criteria decision-making methods, this research employs a hybrid MCDM framework, integrating WASPAS and BWM to provide a more comprehensive and robust evaluation of the COVID-19 vaccine supply chain barriers and mitigation strategies. This combined approach allows for a better understanding of the relative importance of barriers and the prioritisation of strategies to address them, offering valuable insights for policy-makers and supply chain managers. Additionally, the contextual application of the proposed framework to a selected country provides practical implications that can be adapted and applied to other regions facing similar challenges in the COVID-19 vaccine distribution network. The results suggest practical implications for government and health systems worldwide to improve VSC for the COVID-19 outbreak.

4.4 Managerial Implications

This research has significant consequences for managers and policymakers. Managers, politicians, and governments will determine which barriers may be given less attention to and which should receive more attention after they have a good grasp of COVID-19 VSC barriers. Failure to overcome the barriers mentioned might result in serious repercussions, some of which various nations have already experienced. Production delays and blood clot occurrences associated with the AstraZeneca vaccine, for example, have already disrupted vaccine distribution in the European Union (Wise, 2021). This is one of the immediate consequences of the study's most major issue.

Furthermore, an analysis of vaccination programmes across various countries reveals the critical role of coordinated efforts between governmental bodies and local organisations. Freed (2021) emphasises that the lack of proper collaboration with local stakeholders remains one of the most significant barriers to the success of vaccination initiatives. This finding aligns with the conclusions of the study, which underscore the importance of fostering effective partnerships at all levels of governance. Additionally, while "insufficient positive vaccine marketing" (B22) ranks as the ninth most significant obstacle, it holds substantial implications for vaccine acceptance. Inadequate communication efforts can contribute to vaccine hesitancy, which in turn may impede the achievement of herd im-munity and hinder the complete vaccination of the population (D*ROR et al*., 2020). This suggests that effective management of the COVID-19 vaccine supply chain (VSC) necessitates overcoming these challenges through targeted strategies, ensuring that each identified barrier is addressed to facilitate the global vaccination effort.

The suggested BWM-WASPAS methodology for identifying and analysing VSCBs and ranking alternatives may assist policymakers in developing flexible vaccine distribution methods while minimising negative impacts on sustainable development objectives. Governments from various nations might also examine the relationships between these barriers to implement their immunisation programmes properly. Overcoming the 15 COVID-19 VSC barriers identified in this research will help nations throughout the globe achieve herd im-munity and swiftly recover from the pandemic's economic and social losses. Investment in vaccine manufacturing enterprises, for example, may defend against rising inequality as a result of vaccine nationalism and so promote sustainable development to minimise disparities within and between nations. Peace, justice, and strong institutions will be easier to achieve with such an investment. Overcoming the barriers would need the active participation of governments and vaccine producers in enhancing the vaccine supply chain, which may encourage collaboration. More vaccine production businesses will lower vaccination prices and make vaccines cheaper in poor nations, assisting in achieving the poverty reduction target. Cities and communities may be more sustainable if they invest in data technology for precise demand forecasts and monitoring of vaccinated populations. By mandating supply chain-wide cooperation of VSC members to put forth new creative solutions to protect the vaccinated population against any non-vaccinated population, such investment may also encourage industry, innovation, and infrastructure.

Furthermore, by overcoming consumer aversion to vaccination and establishing positive vaccine marketing efforts, mass vaccination may be ensured, contributing to the general population's excellent health and well-being. It may also help to improve education by encouraging students to return to schools. By addressing these impediments, we may come closer to achieve zero hunger by preventing the death of earning family members. As a result, it is critical to examine these restrictions thoroughly and comprehend their ramifications. This research aids in a better understanding of COVID-19 VSCBs, allowing for a speedier recovery from the pandemic.

Conclusions

The COVID-19 pandemic has had a devastating impact on the global economy, severely threatening humanity's long-term survival. Vaccination has emerged as a crucial tool to mitigate the spread of the virus and save lives. Therefore, mass vaccination against COVID-19 is an urgent and essential strategy for pandemic recovery. However, the development, production, distribution, and administration of vaccines present significant challenges. The role of the Vaccine Supply Chain (VSC) is to ensure the timely and accurate delivery of vaccines to the right locations in the appropriate quantities. Governments must develop evidence-based policies to facilitate universal vaccination and ensure equitable access to COVID-19 vaccines. This paper aimed to examine and categorise the barriers faced by the COVID-19 VSC and identify strategies to overcome these challenges in the fight against the global pandemic. The identification of key VSC barriers is essential before vaccine distribution to the general public, as addressing these obstacles is critical to the design of efficient immunization programs.

In this study, 15 COVID-19 VSC barriers (VSCBs) identified through literature review and expert opinions are presented, along with seven strategies to overcome these barriers. These strategies are ranked using the WASPAS method to assess their effectiveness in improving the overall COVID-19 VSC. The analysis was conducted in two stages. First, the weights of the identified VSCBs were calculated using the Best-Worst Method (BWM), which provides an evaluation of the most significant barriers hindering the VSC process. The findings indicate that the most critical barriers in the COVID-19 VSC are the "lack of vaccine monitoring bodies (B52)", "challenges in monitoring and controlling vaccine temperature (B42)", "vaccine cost and insufficient financial support for vaccine procurement (B11)", and "limited number of vaccine manufacturing companies (B12)". Second, the WASPAS method was employed to rank the strategies for overcoming these barriers. The results reveal that the primary strategies for effectively managing the COVID-19 VSC include fostering collaboration, cooperation, coordination, and integration among organisations (ST5), as well as developing a robust research and development plan (ST4). These strategies are pivotal in overcoming the VSC barriers and ensuring the successful vaccination of populations, ultimately supporting the economic progress of nations.

However, this research has some limitations. Given the relatively small number of experts involved, future studies should incorporate a larger sample of stakeholders and decision-makers. In addition, further research could focus on validating the results of this study by examining its practical applicability, reliability, and sensitivity. Future studies might also explore additional challenges faced at different stages of the VSC, including vaccine growth, manufacturing, distribution, and management. Furthermore, the barriers identified in this study predominantly reflect the perspectives of experts from low- and middle-income countries, which may limit the generalizability of the findings. Therefore, future research should include experts from high-income and developing countries to ensure a more comprehensive understanding of the VSC. Finally, for a more robust VSC model, future studies may consider incorporating hesitant fuzzy sets and interpretive structural modeling (ISM) methodologies to refine the decision-making process in complex scenarios.

Literature

Abbasi, B., Fadaki, M., Kokshagina, O., Saeed, N., Chhetri, P. (2020), *Modeling vaccine allocations in the COVID-19 pandemic: A case study in Australia*, available at SSRN 3744520, http://dx.doi.org/10.2139/ssrn.3744520.

Abbasi, S., Zahmatkesh, S., Bokhari, A., Hajiaghaei-Keshteli, M. (2023), "Designing a vaccine supply chain network considering environmental aspects", *Journal of Cleaner Production*, 417, 137935, https://doi.org/10.1016/j.jclepro.2023.137935.

Ahmadi, H.B., Kusi-Sarpong, S., Rezaei, J. (2017), "Assessing the social sustainability of supply chains using Best Worst Method", *Resources, Conservation and Recycling*, Vol. 126, pp.99-106. https://doi.org/10.1016/j.resconrec.2017.07.020.

Antal, C., Cioara, T., Antal, M., Anghel, I. (2021), "Blockchain platform for COVID-19 vaccine supply management", *IEEE Open Journal of the Computer Society*, Vol. 2, pp.164-178, https://doi.org/10.1109/OJCS.2021.3067450.

Arslan, Ö., Cebi, S. (2024), "A novel approach for multi-criteria decision making: extending the WASPAS method using decomposed fuzzy sets", *Computers & Industrial Engineering*, Vol. 196, October, 110461, https://doi.org/10.1016/j.cie.2024.110461.

Bhattacharya, S., Halder, R., Das, M., Mallick, B. (2024), "Prioritization of the barriers of vaccine supply chain in India", *Accounting*, Vol. 10, No 1, pp.41-48.

Bozorgmehr, K., Jahn, R., Stuckler, D., McKee, M. (2021), "Free licensing of vaccines to end the COVID-19 crisis", *Lancet*, Vol. 397, No 10281, pp.1261-1262.

Burgos, R.M., Badowski, M.E., Drwiega, E., Ghassemi, S., Griffith, N., Herald, F., Johnson, M., Smith, R.O., Michienzi, S.M. (2021), "The race to a COVID-19 vaccine: Opportunities and challenges in development and distribution", *Drugs in Context*, 10, https://doi.org/10.7573/dic.2020-12-2.

Cano-Marin, E., Ribeiro-Soriano, D., Mardani, A., Gonzalez-Tejero, C.B. (2023), "Exploring the challenges of the COVID-19 vaccine supply chain using social media analytics: a global perspective", *Sustainable Technology and Entrepreneurship*, Vol. 2, No 3, 100047, https://doi.org/10.1016/j.stae.2023.100047.

Chakraborty, S., Mali, K. (2021), "SuFMoFPA: A superpixel and meta-heuristic based fuzzy image seg-mentation approach to explicate COVID-19 radiological images", *Expert Systems with Applications*, Vol. 167, 114142, https://doi.org/10.1016/j.eswa.2020.114142.

Chakraborty, S., Raut, R.D., Rofin, T.M., Chakraborty, S. (2025), "A narrative literature review on optimization of manufacturing processes using weighted aggregated sum product assessment (WASPAS) method", *OPSEARCH*, Vol. 62, pp.1616-1640.

Chen, S.-I., Norman, B.A., Rajgopal, J., Lee, B.Y. (2015), "Passive cold devices for vaccine supply chains", *Annals of Operations Research*, Vol. 230, No 1, pp.87-104.

Chojnacky, M.J., Miller, W.M., Strouse, G.F. (2013), "Methods for accurate cold-chain temperature monitoring using digital data-logger thermometers", in: AIP Conference Proceedings, American Institute of Physics, Vol. 1552, No 1, pp.1014-1019.

Corrente, S., Greco, S., Rezaei, J. (2024), "Better decisions with less cognitive load: The Parsimonious BWM", *Omega*, Vol. 126, July, 103075, https://doi.org/10.1016/j.omega.2024.103075.

Dai, D., Wu, X., Si, F. (2021), "Complexity analysis of cold chain transportation in a vaccine supply chain considering activity inspection and time-delay", *Advances in Difference Equations*, Vol. 39, https://doi.org/10.1186/s13662-020-03173-z.

Dey, S., Kurbanzade, A.K., Gel, E.S., Mihaljevic, J., Mehrotra, S. (2024), "Optimization modeling for pandemic vaccine supply chain management: A review and future research opportunities", *Naval Re-search Logistics (NRL)*, Vol. 71, No 7, pp.976-1016.

Dizbay, İ.E., Öztürkoğlu, Ö. (2020), "Determining significant factors affecting vaccine demand and factor relationships using fuzzy DEMATEL method", *International Conference on Intelligent and Fuzzy Systems*, pp.682-689.

D*ROR*, A.A., Eisenbach, N., Taiber, S., Morozov, N.G., Mizrachi, M., Zigron, A., Srouji, S., Sela, E. (2020), "Vaccine hesitancy: the next challenge in the fight against COVID-19", *European Journal of Epidemiology*, Vol. 35, No 8, pp.775-779.

Ecer, F., Murat, T., Dinçer, H., Yüksel, S. (2024), "A fuzzy BWM and MARCOS integrated framework with Heronian function for evaluating cryptocurrency exchanges: a case study of Türkiye", *Financial In-novation*, Vol. 10, No 1, 31, https://doi.org/10.1186/s40854-023-00543-w.

Freed, G.L. (2021), "Actionable lessons for the US COVID vaccine program", *Israel Journal of Health Policy Research*, Vol. 10, No 1, 14, https://doi.org/10.1186/s13584-021-00452-2.

Gao, F., Han, M., Wang, S., Gao, J. (2024), "A novel Fermatean fuzzy BWM-VIKOR based multi-criteria decision-making approach for selecting health care waste treatment technology", *Engineering Applications of Artificial Intelligence*, Vol. 127, 107451, https://doi.org/10.1016/j.engappai.2023.107451.

Gupta, H., Barua, M.K. (2016), "Identifying enablers of technological innovation for Indian MSMEs using Best Worst Method", *International Journal of Production Economics*, 173, pp.291–303, https://doi.org/10.1016/j.ijpe.2015.12.006.

Gupta, H., Barua, M.K. (2018), "A BWM-based approach for evaluating enablers of sustainable supply chain practices in Indian oil and gas industry", *Journal of Cleaner Production*, Vol. 190, pp.524-541, https://doi.org/10.1016/j.jclepro.2018.04.136.

Goodwin, A. (2021), "Vaccine set to be a game-changer in 2021", *Economic Outlook*, Vol. 45, No 1, pp.5-8, https://doi.org/10.1111/1468-0319.12528.

Henao-Restrepo, A.M., Longini, I.M., Egger, M., Dean, N.E., Edmunds, W.J., Camacho, A., Carroll, M.W., Doumbia, M., Draguez, B., Duraffour, S. (2015), "Efficacy and effectiveness of an rVSV-vectored vaccine expressing Ebola surface glycoprotein: interim results from the Guinea ring vaccination cluster-randomised trial", *The Lancet*, Vol. 386, No 9996, pp.857-866.

Hodgson, S.H., Mansatta, K., Mallett, G., Harris, V., Emary, K.R.W., Pollard, A.J. (2021), "What defines an efficacious COVID-19 vaccine? A review of the challenges assessing the clinical efficacy of vaccines against SARS-CoV-2", *The Lancet Infectious Diseases*, Vol. 21, No 2, pp.e26–e35.

Hu, H., Xu, J., Liu, M., Lim, M.K. (2023), "Vaccine supply chain management: An intelligent system utilizing blockchain, IoT and machine learning", *Journal of Business Research*, Vol. 156, February, 113480, https://doi.org/10.1016/j.jbusres.2022.113480.

Ivanov, D., Dolgui, A. (2021), "OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: Managerial insights and research implications", *International Journal of Pro-duction Economics*, Vol. 232, February, 107921, https://doi.org/10.1016/j.ijpe.2020.107921.

Kargar, B., MohajerAnsari, P., Büyüktahtakın, İ.E., Jahani, H., Talluri, S. (2024), "Data-driven modeling for designing a sustainable and efficient vaccine supply chain: A COVID-19 case study", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 184, April, 103494, https://doi.org/10.1016/j.tre.2024.103494.

Kartoğlu, Ü., Nelaj, E., Maire, D. (2010), "Improving temperature monitoring in the vaccine cold chain at the periphery: An intervention study using a 30-day electronic refrigerator temperature logger (Fridge-tag®)", *Vaccine*, Vol. 28, No 24, pp.4065-4072.

Khubchandani, J., Sharma, S., Price, J.H., Wiblishauser, M.J., Sharma, M., Webb, F.J. (2021), "COVID-19 vaccination hesitancy in the United States: a rapid national assessment", *Journal of Community Health*, Vol. 46, No 2, pp.270-277.

Kim, J.H., Marks, F., Clemens, J.D. (2021), "Looking beyond COVID-19 vaccine phase 3 trials", *Nature Medicine*, Vol. 27, No 2, pp.205–211.

Lee, B.Y., Haidari, L.A. (2017), "The importance of vaccine supply chains to everyone in the vaccine world", *Vaccine*, Vol. 35, No 35, pp.4475-4479.

Lin, Q., Zhao, Q., Lev, B. (2020), "Cold chain transportation decision in the vaccine supply chain", *European Journal of Operational Research*, Vol. 283, No 1, pp.182-195.

Mehra, R., Ray, A., Das, S., Chowdhury, B.K., Koshal, S.S., Hora, R., Kumari, A., Kaur, A., Quadri, S.F., Roy, A.D. (2024), "Enablers and barriers to rotavirus vaccine coverage in Assam, India-A qualitative study", *Vaccine: X*, Vol. 18, June, 100479, https://doi.org/10.1016/j.jvacx.2024.100479.

Mohammadi, M., Rezaei, J. (2019), "Bayesian Best–Worst Method: A Probabilistic Group Decision-Making Approach", *Omega*, Vol. 96, October, 102075, https://doi.org/10.1016/j.omega.2019.02.009.

Narayanamurthy, G., Tortorella, G. (2021), "Impact of COVID-19 outbreak on employee performance–moderating role of industry 4.0 base technologies", *International Journal of Production Economics*, Vol. 234, 108075, https://doi.org/10.1016/j.ijpe.2021.108075.

Ocampo, L., amagishi, K. (2020), "Modeling the lockdown relaxation protocols of the Philippine government in response to the COVID-19 pandemic: An intuitionistic fuzzy DEMATEL analysis", *So-cio-Economic Planning Sciences*, Vol. 72, Article No 100911.

Pagliusi, S., Jarrett, S., Hayman, B., Kreysa, U., Prasad, S.D., Reers, M., Thai, P.H., Wu, K., Zhang, Y.T., Baek, Y.O. (2020), "Emerging manufacturers engagements in the COVID−19 vaccine research, development and supply", *Vaccine*, Vol. 38, No 34, pp.5418-5423.

Ratzan, S.C., Bloom, B.R., El-Mohandes, A., Fielding, J., Gostin, L. O., Hodge, J. G., Hotez, P., Kurth, A., Larson, H.J., Nurse, J. (2019), "The Salzburg statement on vaccination acceptance", *Journal of Health Communication*, Vol. 24, No 5, pp.581-583.

Rele, S. (2021), "COVID-19 vaccine development during pandemic: gap analysis, opportunities, and impact on future emerging infectious disease development strategies", *Human Vaccines & Immunotherapeutics*, Vol. 17, No 4, pp.1122–1127.

Rezaei, J. (2016), "Best–Worst Multi-Criteria Decision-Making Method: Some Properties and a Linear Model", *Omega*, Vol. 64, October, pp.126-130, https://doi.org/10.1016/j.omega.2015.12.001.

Rezaei, J., Nispeling, T., Sarkis, J., Tavasszy, L. (2016), "A Supplier Selection Life Cycle Approach Integrating Traditional and Environmental Criteria Using the Best–Worst Method", *Journal of Cleaner Production*, 135, pp.577-588, https://doi.org/10.1016/j.jclepro.2016.06.125.

Richards, A.D. (2020), "Ethical guidelines for deliberately infecting volunteers with COVID-19*", Journal of Medical Ethics*, Vol. 46, No 8, pp.502–504.

Rosen, B., Waitzberg, R., Israeli, A., Hartal, M., Davidovitch, N. (2021), "Addressing vaccine hesitancy and access barriers to achieve persistent progress in Israel's COVID-19 vaccination program", *Israel Journal of Health Policy Research*, Vol. 10, 43, https://doi.org/10.1186/s13584-021-00481-x.

Sahebi, I., Masoomi, B., Ghorbani, S., Uslu, T. (2019), "Scenario-based designing of closed-loop supply chain with uncertainty in returned products", *Decision Science Letters*, Vol. 8, No 4, pp.505-518.

Shahrabi-Farahani, S., Hafezalkotob, A., Mohammaditabar, D., Khalili-Damghani, K. (2024), "Selection of sustainable industrial livestock site using the R-Number GIS-MCDM method: A case study of Iran", *Environmental and Sustainability Indicators*, Vol. 22, June, 100362, https://doi.org/10.1016/j.indic.2024.100362.

Shamsi, N., Torabi, S.A. (2018), "Vaccine supply management", in: C. Kahraman, Y. Ilker Topcu (eds.), *Operations Research Applications in Health Care Management,* Springer, pp.267-294.

Sahoo, S.K., Goswami, S.S. (2023), "A comprehensive review of multiple criteria decision-making (MCDM) methods: advancements, applications, and future directions", *Decision Making Advances*, Vol. 1, No 1, pp.25-48.

Shervani, Z., Khan, I., Khan, T., Qazi, U.Y. (2020), "COVID-19 vaccine", *Advances in Infectious Diseases*, Vo. 10, No 03, pp.195-210, https://doi.org/10.4236/aid.2020.103020.

Shiri, M., Fattahi, P., Sogandi, F. (2024), "An integrated blockchain-enabled multi-channel vaccine supply chain network under hybrid uncertainties", *Scientific Reports*, Vol. 14, No 1, 22829, https://doi.org/10.1038/s41598-024-67071-0 .

Singh, T. (2024), "Entropy weighted WASPAS and MACBETH approaches for optimizing the performance of solar water heating system", *Case Studies in Thermal Engineering*, Vol. 53, January,103922, https://doi.org/10.1016/j.csite.2023.103922.

Valizadeh, J., Boloukifar, S., Soltani, S., Hookerd, E.J., Fouladi, F., Rushchtc, A.A., Du, B., Shen, J. (2023), "Designing an optimization model for the vaccine supply chain during the COVID-19 pandemic", *Expert Systems with Applications*, Vol. 214, 119009, https://doi.org/10.1016/j.eswa.2022.119009.

Warren, G.W., Lofstedt, R. (2021), "COVID-19 vaccine rollout risk communication strategies in Europe: a rapid response", *Journal of Risk Research*, Vol. 24, No 3-4, pp.369-379.

Weintraub, R.L., Subramanian, L., Karlage, A., Ahmad, I., Rosenberg, J. (2021), "COVID-19 Vaccine To Vaccination: Why Leaders Must Invest In Delivery Strategies Now: Analysis describe lessons learned from past pandemics and vaccine campaigns about the path to successful vaccine delivery for COVID-19", *Health Affairs*, Vol. 40, No 1, pp.33-41.

Wise, J. (2021), "COVID-19: European countries suspend use of Oxford-AstraZeneca vaccine after reports of blood clots", *British Medical Journal Publishing Group*, 372, https://doi.org/10.1136/bmj.n699.

Yang, S., Liao, H., Wu, X. (2025), "Prescriptive analytics for dynamic multi-criterion decision making considering learned knowledge of alternatives", *Expert Systems with Applications*, 268, 126350, https://doi.org/10.1016/j.eswa.2024.126350.

Yu, D.E.C., Razon, L.F., Tan, R.R. (2020), "Can global pharmaceutical supply chains scale up sustainably for the COVID-19 crisis?", *Resources, Conservation, and Recycling*, 159, 104868, https://doi.org/10.1016/j.resconrec.2020.104868.

Zavadskas, E.K., Turskis, Z., Antucheviciene, J., Zakarevicius, A. (2012), "Optimization of weighted aggregated sum product assessment", *Elektronika ir Elektrotechnika*, Vol. 122, No 6, pp.3-6.

Zhu, G., Chou, M. C., Tsai, C.W. (2020), "Lessons learned from the COVID-19 pandemic exposing the shortcomings of current supply chain operations: A long-term prescriptive offering", *Sustainability*, Vol. 12, No 14, 5858, https://doi.org/10.3390/su12145858.

HIBRIDINĖ MCDM SISTEMA, SKIRTA ĮVEIKTI KLIŪTIS COVID-19 VAKCINŲ TIEKIMO GRANDINĖJE

Shahryar Ghorbani, Figen Yıldırım, Ali Altuğ Biçer, Edmundas Kazimieras Zavadskas, Jurgita Antuchevičienė, Reza Rostamzadeh

Santrauka. COVID-19 pandemija sukėlė precedento neturinčių iššūkių visame pasaulyje, o vakcinų tiekimo grandinė yra itin svarbi siekiant sumažinti viruso plitimą. Šiame straipsnyje nagrinėjamos svarbiausios COVID-19 vakcinų tiekimo grandinės kliūtys, nustatomos šių kliūčių įveikimo strategijos ir siūlomas hibridinis daugiakriteris sprendimų priėmimo metodas (angl. *multi-criteria decision-making,* MCDM) šių strategijų prioritetui nustatyti. Naudojant geriausiojo ir blogiausiojo atvejų metodą (angl. *Best – Worst Method*, BWM) kliūčių svarbai nustatyti ir svertinio agreguoto sumos ir sandaugos įvertinimo metodą (angl. *Weighted Aggregate Sum Product Assessment*, WASPAS) strategijoms reitinguoti, šiame tyrime atskleidžiama, kad didžiausios kliūtys yra vakcinų temperatūros stebėjimo ir kontrolės, šaltosios grandinės logistikos priežiūros ir išlaidų bei neoptimalių imunizacijos biudžetų valdymo iššūkiai. Rezultatai atskleidė, kad veiksmingiausia šių kliūčių įveikimo strategija yra bendradarbiavimo ir koordinavimo tarp organizacijų skatinimas. Šis tyrimas suteikia praktinių įžvalgų politikos formuotojams, sveikatos priežiūros sistemoms ir vakcinų platintojams, kaip padidinti COVID-19 vakcinų tiekimo grandinės efektyvumą ir atsparumą, prisidedant prie pasaulinių vakcinacijos pastangų. Tyrimo įžvalgos gali būti naudingos planuojant būsimą pandemijos atsaką ir siūlant strategijas, kaip sukurti tvaresnes ir prisitaikančias vakcinų tiekimo grandines.

Reikšminiai žodžiai: COVID-19 vakcinų tiekimo grandinė; vakcinų platinimo iššūkiai; daugiakriteris sprendimų priėmimas (multi-criteria decision-making, MCDM); geriausiojo ir blogiausiojo atvejo metodas (Best – Worst Method, BWM); svertinio agreguoto sumos ir sandaugos įvertinimo metodas (Weighted Aggregate Sum Product Assessment, WASPAS); vakcinų logistikos optimizavimas; tiekimo grandinės atsparumas.

Appendix 1

Table 2A. List of Barriers to COVID-19 VSC

Code	Barriers	Descriptions	References
B1	Vaccination costs and a lack of financial assistance in purchasing vaccines.	To effectively control the potentially harmful COVID-19 pandemic we need an affordable vaccine. Global vaccine programmes face financial obstacles since high production costs prevent adequate funding for vaccine purchase, facility operations and maintenance of vaccine storage systems.	Expert panel
B2	Limited vaccine production organisation	A significant number of vaccinations are required to inoculate the whole world's population. A major problem is the small number of businesses that can effectively create effective vaccines, limiting immunisation efforts across the globe.	Pagliusi *et al*. (2020)
B3	Unpredictability of global demand	Four factors including per capita income and vaccine convictions and medical staff knowledge and regional urbanisation and vaccination missions can affect vaccine demand levels. The absence of foresight into the factors noted above threatens to diminish the effectiveness of COVID-19 vaccination strategies.	Dizbay and Öztürkoğlu (2020)
B4	Unwillingness of consumers to be vaccinated	Consumers may reject vaccines due to concerns about vaccine adverse effects, societal orthodoxy, disinformation, and vaccination-related negative views or skepticism.	Khubchandani *et al*. (2021)
B5	Inadequate positive vaccine marketing	Positive vaccination marketing is crucial for COVID-19 vaccine adoption. An insufficient positive vaccine promotion may influence a negative public impression of COVID-19 vaccinations.	Expert panel
B6	Unavailability of volunteers for vaccine trials	Since stages II and III require human tests, a shortage of volunteers might severely hinder the growth of COVID-19 vaccines.	Richards (2020)
B7	A long-distance separate vaccine stores and vaccination sites.	Long distances between vaccine supplies and vaccination sites might have a detrimental impact on vaccine distribution.	Antal *et al*. (2021)
B8	Inadequate planning and scheduling	Immunisation enrollment, vaccine purchasing, storage, and distribution may be affected by a lack of adequate planning and scheduling.	Antal *et al*. (2021)
B9	Increase in acquisition lead time	Delays in purchase choices may lengthen the acquisition process and impede the vaccine's timely dissemination.	Expert panel
B10	Inadequate storage systems	Due to a lack of suitable storage methods in distant places, vaccine distribution may be delayed, reducing the efficiency of the COVID-19 VSC.	Rosen *et al*. (2021)
B11	Difficulties in monitoring and controlling vaccine temperature	Temperature is a factor in several COVID-19 vaccinations. Inability to keep vaccines at the correct temperature when moving them from makers to customers may diminish VS's effectiveness, particularly in tropical areas.	Lin *et al*., (2020)
B12	Difficulty of tracking the vaccinated population	The COVID-19 vaccine's transparency and equitable distribution may be harmed by the difficulties of following the vaccinated population. Countries without a central population health registry will find it challenging to track and monitor the overall number of people who have been vaccinated.	Hodgson *et al*. (2021)
B13	Ineffective coordination with local groups	By establishing communication gaps, improper cooperation with local healthcare groups may obstruct vaccines' quick supply and distribution. Working with local groups to appropriately distribute the COVID-19 vaccination and timely reaction is common.	Expert panel
B14	Lack of vaccination monitoring organisations	In the VSC, a lack of vaccine monitoring bodies may obstruct vaccine purchasing, distribution, monitoring, and transparency.	Expert panel

B15	Weak communication amongst the VSC members	Global supply networks are experiencing substantial disruptions, and a lack of communication among supply chain partners might obstruct the appropriate manufacture and delivery of the COVID-19 vaccine.	Zhu *et al.*, (2020)

Source: created by the authors.