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An integrated framework for managing vaccine supply chain shortages in the child immunization program of India

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ABSTRACT

Ensuring a consistent supply of vaccines from manufacture to distribution, storage, and administration relies on efficient management of the Vaccine Supply Chain (VSC). However, in recent years, vaccine shortages have emerged as a major issue for vaccine producers and child immunization programs, especially in low- and middle-income countries, which hampers VSC overall performance. This study aims to address the ongoing problem of vaccine shortages in India's child immunization program by identifying the main causes and investigating possible solutions to address the shortage issue. To do this, we propose an integrated framework that combines the Analytic Hierarchy Process (AHP) and Complex Proportional Assessment with Grey Theory (COPRAS-G) methodologies. This framework yields 12 potential solutions for the 10 issues causing shortages. We show that demand uncertainty is the primary cause of vaccine shortages and that a better monitoring system is necessary to detect and treat shortages in a timely manner. To validate the stability of the results, we run a Monte Carlo simulation using a uniform probability distribution on the interval [0, 1]. The results of this study will provide valuable insights for policymakers on how to effectively manage the vaccine shortage issue and improve the performance of child immunization programs.

1. Introduction

One of the primary goals of child immunization programs is to guarantee that there is an adequate supply of life-saving vaccines at healthcare facilities so that all children get their doses as scheduled. The scarcity of vaccines not only hinders the timely administration of vaccinations to children but also poses a significant threat to their overall well-being. Despite the concerted efforts of immunization authorities and international health organizations such as the World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF), vaccine shortages continue to persist in both developed and developing nations. According to Vaccine Supply Chain (VSC) experts, limited vaccine availability leads to a delay in the provision of routine immunization services and a surge in demand (Gupta, Nair, Arora, & Ganguly, 2013; Lydon et al., 2017; Milstien & Lambert, 2002; Lee and Haidari, 2017). Consequently, this situation has a persistent impact on the effectiveness of immunization programs. Periods of limited vaccine availability impedes the regular administration of vaccine doses to children. Once the shortage resolves, immunization authorities must effectively manage the task of providing vaccinations to both the overall population in need and the specific group of population who missed their scheduled doses during the shortage period (Chandra & Kumar, 2021; IFPMA, 2017; Luzze et al., 2017). Effective management of vaccine shortages is therefore crucial for decision-makers, as the overall performance of the child immunization program heavily depends on how well these shortages are addressed.

The occurrence of vaccine shortages is characterized by a country's inability to satisfy its national requirements, which include the population and buffer. Shortages can occur at various points in supply chains, ranging from the supplier to the manufacturer and extending to distribution. Shortages can occur not only once a year but also frequently and globally, affecting countries of all income levels and regions (Cernuschi et al., 2018; IFPMA, 2017). For example, a flu outbreak in the United

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States resulted in a shortage of flu vaccine, which led to the deaths of many children and infants (McNeil Jr, 2018). A global shortage led to a shortage of the Inactivated Poliomyelitis Vaccine (IPV) in India (Sutter & Cochi, 2019). The global shortage of the hepatitis B vaccine in 2017 is an example that highlights how manufacturers are facing difficulties in producing enough vaccines to meet global demand (Perrett et al., 2019).

According to Liu & Lou (2022), vaccine shortages can arise from a range of constraints, such as production and supply interruptions, unanticipated high demand, and insufficient resources, including healthcare capacity for vaccine administration. Manufacturing shortages caused by production issues, such as yield uncertainty, can significantly disrupt the entire supply chain. Angelus & Özer (2022) note that low and unpredictable production yields have always been a major challenge for large-scale vaccine manufacturing companies. The case of AstraZeneca serves as an example of a vaccine manufacturer that encountered challenges in meeting the required dosage of COVID-19 vaccines for the European Union, owing to uncertainties in yield. Developing nations often experience a shortage of life-saving vaccines, including hepatitis and Diphtheria-Pertussis-Tetanus (DPT), due to yield uncertainty (Chandra & Kumar, 2018; Chick et al., 2008). Conversely, a limited supply and shortages due to increased vaccination demand can cause a short-term disruption in the supply chain. For instance, the first introduction of the COVID-19 vaccine led to a surge of individuals who eagerly rushed to health centers to receive their vaccine dose. This sudden influx caused a temporary shortage in the VSC. Despite the scenarios outlined above, it is probable that vaccination rates will experience a decline. A well-managed supply chain, with proper strategies, can effectively mitigate the negative impacts of vaccine shortages on vaccination rates. For instance, it is always helpful for decision-makers to employ measures like keeping a buffer stock to meet demand during shortages or pooling inventories amongst several healthcare facilities operating in different locations to lessen risk and improve service quality (Wang et al., 2023).

Filia et al. (2022) point out that in several European countries, only a small number of nations have expert committees or established processes to address stockouts or shortages. Lydon et al. (2017) point out that in 96% of shortage cases, district-level stockouts would disrupt immunization services. Since the vaccine shortages depend upon the vaccine type and other internal and external factors, the present study centers on identifying specific solutions that can aid policymakers in alleviating the adverse effects of vaccine shortages of life-saving vaccines (vaccines given to children up to 5 years and pregnant women) on child immunization programs. More specifically, our suggested framework is an integrated approach that primarily focuses on India's immunization program, focusing on the root causes of childhood vaccine shortages as well as solutions to address them.

India currently possesses the highest capacity to produce WHO-prequalified vaccines globally, owing to the country's burgeoning vaccine industry and state of the art manufacturing facilities. India, despite being a prominent manufacturing hub, exhibits suboptimal child vaccination rates in comparison to global benchmarks. The principal factor contributing to the inadequate immunization coverage in India is the constraints in vaccine distribution, the public health delivery system, and vaccine supply (Chandra & Kumar, 2021; Rai et al., 2022; A. K. Yadav et al., 2023). Given these considerations, the present study poses the following research questions:

RQ1. *What are the significant factors contributing to vaccine shortages in India's child immunization program?*

RQ2. *What are the potential solutions to address shortages in immunization programs?*

RQ3. *Can a Multi-Criteria Decision-Making (MCDM) framework assist supply chain decision-makers in minimizing shortages and enhancing system performance?*

To investigate the research questions, this study outlines 10 causes or criteria that lead to the occurrence of vaccine shortages, along with 12 solutions or alternatives to alleviate the issue of shortage. The causes and solutions presented in this study are based on a comprehensive literature review, a field survey conducted across 3 Indian states, and insights provided by area experts. We use an integrated framework consisting of two domains of methods—the Analytic Hierarchy Process (AHP), which uses pairwise comparison to produce relative weights of the causes, and the Complex Proportional Assessment with Grey Theory (COPRAS-G), which employs Grey System Theory (GST) to rank the solutions according to their respective utility values.

The primary goal of integrating AHP with COPRAS-G is to improve decision-making by incorporating expert opinions into AHP and generating more accurate criteria weights. This ensures that the derived weights are logically coherent and reflect the relative importance of the criteria precisely, as opposed to relying on randomly generated weights that may not accurately reflect the true significance of each criterion. We validate our findings using Monte Carlo simulation under a uniform probability distribution with a domain [0, 1]. To the best of our knowledge, no such study exists that investigates all VSC components that contribute to shortages in the immunization programs. Our study can be classified as state of the art in the vaccine and vaccinology fields, as no prior studies have explored strategies to boost VSC efficiency by accounting for shortage factors using any analytical method.

Moreover, we summarize our main contributions as follows. Firstly, we emphasize the importance of vaccine shortages in India's child vaccination program's success, a factor that policymakers generally overlook when devising policies in low- and middle-income countries. Secondly, by identifying and ranking the causes and solutions for vaccine shortages, our framework provides a clear roadmap for decision-makers to prioritize their efforts on the right direction. This can help streamline the VSC and ensure that resources are allocated efficiently to address the most pressing issues. Thirdly, our focus on ranking specific solutions demand forecasting and improved monitoring systems to measure shortages highlights the importance of accurate data and real-time tracking in managing vaccine distribution, which can be applied to other areas of public health logistics. Lastly, our work can serve as a foundation for future research, encouraging scholars, practitioners, and academicians to explore additional factors affecting VSC in India and develop more comprehensive solutions. By addressing both immediate and long-term challenges of VSC shortages, our contributions can help policymakers to create a more resilient and efficient vaccine distribution system in India to improve child immunization program performance.

Subsequent sections of the paper are structured in the following way. Section 2 provides an overview of the existing literature on VSC and vaccine shortages and discusses research gaps and major contributions of the paper. Section 3 presents an overview of the methodology used in our study. Section 4 outlines an integrated framework that is utilized to ascertain the underlying causes of vaccine shortages and to propose potential solutions. Results are presented in Section 5, while Section 6 provides a discussion of the results and their implications for managers. Finally, Section 7 comprises conclusion, limitations, and future scope of the study.

2. Literature review

Vaccine shortages represent a substantial risk to public health since they can lead to lower immunization rates, an increase in the prevalence of diseases that are readily preventable with vaccination, and an increase in VSC costs (Adida, Dey, & Mamani, 2013; Duijzer, van Jaarsveld, Wallinga, & Dekker, 2018; Liu & Lou, 2022). In low- and middle-income countries, where access to vaccines is already limited, stockouts increase existing inequalities in healthcare delivery and broaden disparities in health outcomes. Addressing the root causes of vaccine stockouts is imperative to strengthen healthcare systems and ensure equitable access to life-saving vaccines for all populations (Alam et al., 2021). We focus our literature review on studies that address vaccine shortages in specific regions or globally, examining the reasons for shortages and solutions to enhance VSC efficiency. This review aims to identify the primary causes of vaccine shortages and explore potential solutions to mitigate these issues, particularly within the context of India's child immunization program.

2.1. Vaccine shortages

Vaccine shortages can occur due to a variety of factors, including disruptions in the supply chain, challenges in distribution, and erroneous forecasts of demand. In low- and middle-income nations, the presence of inadequate infrastructure and logistical challenges is particularly noticeable that often leads to stockouts. The risk of stockouts is compounded by a weak healthcare system, inadequate transportation networks, and insufficient storage capacity (Lydon et al., 2017). Furthermore, other issues such as production delays, quality control issues, and cold chain failure can also cause supply shortages (Golan et al., 2021; Preez et al., 2016). Chandra and Kumar (2018) highlight 25 key issues in VSC and indicate that vaccine shortages are one of the primary causes of low child vaccination rates in India. Such stockouts significantly impact public health, increasing disease burden and straining healthcare systems. For instance, stockouts in Sub-Saharan Africa caused measles outbreaks, reversing years of disease control efforts (Zaffran et al., 2013). In Nigeria, routine immunization stockouts led to a permanent loss of demand for essential vaccines (Gooding et al., 2019). In addition, vaccine stockouts have significant economic and social repercussions; they strain healthcare systems and reduce community output due to illness, as demonstrated by the COVID-19 pandemic. Abel et al. (2025) highlight the significant disparities and injustices in vaccine acquisition and distribution that emerged during the COVID-19 pandemic, particularly affecting nations in the Global South. The authors attribute these shortages to stockpiling, vaccine nationalism, and the enforcement of intellectual property rights that limited vaccine manufacturing. Due to vaccine procurement, distribution, and storage issues, Salari & Sazvar (2024) noted that chaotic pandemics and outbreaks cause shortages. They propose using vaccination efficacy-based demand substitution to reduce unmet demand, which can compensate for 60% of shortages with substitutable items, thereby enabling faster immunization.

Shortages can significantly impact immunization rates and the public's faith in vaccination service providers. Liebman et al. (2023) study the effect of shortage and rationing on pediatric VSC performance. A shortage of pediatric vaccines decreased vaccination uptake by 4 percentage points and 26 percentage points, resulting in provider changes, more visits, and adverse spillover effects on other healthcare services. Perrett et al. (2019) study examines hepatitis B vaccine coverage in Wales, UK, and the impact of a worldwide vaccine shortage. They, report that hepatitis B vaccine shortage has reduced the vaccination coverage and public trust. Effective vaccine management is essential to reduce the likelihood of stockouts during outbreaks. Asumah et al. (2023) report the importance of managing vaccine shortages in outbreak situations such as measles. Malembaka et al. (2024) suggest a reduced, single-dose oral cholera vaccine regimen and describe the decision-making process and timing to prevent epidemic illness vaccine shortages. In recent years, the entry of online pharmacy has also created issues in VSC that creates temporary shortages of life-saving vaccines and also impose patients safety risk due to counterfeit drugs. In this context, Liang & Mackey (2012) examined the impact of online pharmacy on the availability of vaccines. They collected data on vaccines that were advertised by online pharmacies, data aggregation sites, and social media platforms. They found that none of the vaccines were VIPPS-accredited, and the majority were on the NABP not recommended list. Some online vendors advertised vaccines as over the counter.

2.2. Demand uncertainty

Vaccine shortages are partly attributable to demand uncertainty. Infectious diseases continuously evolve, making accurate forecasts challenging. Vaccination reluctance and various internal and external factors further complicate demand prediction (Lemmens, Decouttere, Vandaele, & Bernuzzi, 2016; Lin, Zhao, & Lev, 2022). Vaccine shortages may arise from demand exceeding expectations and disruptions in supply or production. A significant challenge for vaccine producers is the unpredictability of demand in case of pandemics or regular immunizations, making it hard to anticipate the timing and location of actual demand (Sayarshad, 2023). Lydon et al. (2017) found that one out of every three WHO Member States experienced vaccine stockouts lasting at least one month each year. Delays in government funding, procurement procedures, and inadequate forecasting and stock management were significant contributors to national-level stockouts. It was also observed that a district-level stockout would disrupt immunization services in 96% of cases (Brooks, Habimana, & Huckerby, 2017; Duijzer, van Jaarsveld, & Dekker, 2018). Kim et al. (2024) design inventory models to address the issues given by variable demand for COVID-19 vaccines, considering factors such as side effects, religious objections, and absenteeism, all of which contribute to the buildup of surplus vaccines.

2.3. Financial instability and irregular supply

Financial instability and irregular supply represent a significant challenge leading to shortages and lower immunization coverage among children (Chandra & Kumar, 2018; Kamara et al., 2008; McQuestion et al., 2011). Osei et al. (2024) indicate that substantial differences in vaccination pricing have led to inequalities, with evidence indicating price discrimination, wherein varying costs are imposed for the same vaccine across different countries and regions. The inequitable pricing of vaccinations, although only one aspect of vaccination campaign expenses, presents significant obstacles to equitable access, particularly in low-income nations, and contributes to vaccine unavailability. The pharmaceutical industry, particularly vaccine production, operates under stringent regulatory and legal oversight. Vaccine manufacturing involves handling live organisms and complex biological processes, leading to development timelines distinct from other sectors (Pagliusi et al., 2020; Ulmer et al., 2006). As result, yield uncertainty is a common cause contributing to vaccine stockouts and immunization programs suspensions (Chick et al., 2017; J. Lee et al., 2021). In this context, Angelus & Özer (2022) highlight that yield uncertainty can lead to shortages and reduced profitability. They suggest optimizing vaccine yield through stochastic modeling and small-scale experimental runs before large-scale production. Real-time data analysis can further improve production processes and revenue. Schnepf (2022) examines how perceived scarcity of COVID-19 vaccines influences individuals' willingness to receive vaccinations. An online experiment with German participants during a nationwide vaccine shortage found that those informed of vaccine scarcity showed higher willingness to get vaccinated compared to those informed of vaccine surplus. Additionally, participants in the scarcity condition exhibited more resentment over discussions on relaxations for vaccinated versus unvaccinated individuals. Filia et al. (2022) reported similar findings in Europe, where supply disruptions and worldwide shortages were common causes of stockouts. The authors also report that less than half of the countries surveyed said that they do not have any sort of plan to improve VSC. Similarly, almost 50% of nations lack formal advice or processes to handle shortages or stockouts.

2.4. Technological infrastructure

Technological infrastructure improvements, such as blockchain and Internet of Things (IoT), offer potential solutions for enhancing VSC efficiency (B. Yong et al., 2020; R. Yong, Zhao, & Tan, 2024). A blockchain-based system can provide critical real-time data on vaccine shortages, including their origin and urgency, enabling improved decision-making and management of VSC challenges (Yadav et al., 2023). Ivanov (2024) suggests leveraging digital supply chain management for resilience. Kumar et al. (2022) find a positive correlation between IoT usage and COVID-19 vaccine supply chain performance. Hu et al. (2023) develop an intelligent VSC management system integrating blockchain, IoT, and machine learning to efficiently address vaccine quality, demand forecasting, and stakeholder trust issues within the VSC. Shiri et al. (2024) propose a blockchain-enabled multi-channel network for pandemic VSC management, enhancing cost-effectiveness and transparency. Antal et al. (2021) propose a blockchain-based system ensuring data integrity and immutability in vaccination beneficiary registration, preventing identity theft and enabling transparent self-reporting of side effects. Chandra & Kumar (2018) study shows that stockouts due to vaccine waste and mismanagement of inventory are significant causes of delays in immunization programs. The introduction of the Electronic Vaccine Intelligence Network (eVIN) in India has improved inventory management and reduced stockouts (Gilbert et al., 2017; Gurnani et al., 2020). Despite progress, VSC faces challenges such as ongoing temperature monitoring, counterfeit products, visibility, and coordination among stakeholders (AbuKhousa, Al-Jaroodi, & Lazarova-Molnar, 2017; Clauson, Breeden, Davidson, & Mackey, 2018; Duijzer, van Jaarsveld, Wallinga, & Dekker, 2018; Hanson, George, Sawadogo, & Schreiber, 2017; Lin, Zhao, & Lev, 2020). Kshetri (2018) raises concerns about IoT device vulnerabilities to hacking. Innovations like eVIN and COWIN (https://www.cowin.gov.in/) have managed inventory and reduced stockouts, but excessive vaccine waste remains a global problem (Abbasi, Zahmatkesh, Bokhari, & Hajiaghaei-Keshteli, 2023; Feddema, Fernald, Schikan, & van de Burgwal, 2023).

2.5. Supply chain contract

Coordinating a VSC under demand and supply uncertainty using the supply chain contracts can be a smart strategy to improve VSC efficiency and reduce shortages risk. In this context, inspired by recurring demand and supply mismatches, Deo & Corbett (2009) study how yield uncertainty, a crucial feature of many manufacturing processes, including influenza vaccine, affects enterprises' strategic behavior. They demonstrate that yield uncertainty can increase industry concentration, lower industry production, and equilibrium consumer surplus. Dai et al. (2016) highlight the shortages problem in the influenza vaccine industry and offer a supply chain contract to enhance VSC performance in an environment of uncertainties in influenza vaccine design, delivery, and demand. Chandra & Vipin (2021) address production yield uncertainty when designing the supply contract for India's child immunization program. They demonstrate that subsidies to manufacturers facing yield uncertainty can lower VSC costs and boost vaccine production. Chick et al. (2017) offer a menu of output-based contracts for influenza vaccination under conditions of yield uncertainty and information asymmetry. Research also explores integrating blockchain technology and artificial intelligence with supply chain contracts to mitigate supply chain shortage risks (Gao et al., 2023). The primary goal of these models is supply chain coordination. Liu et al. (2023) investigate the impact of blockchain technology on VSC members, including consumers, by developing a blockchain-based VSC game model and analyzing VSC blockchain development and coordination strategies. Adhikari et al. (2025) propose a three-level AI-enabled supply chain model encompassing a manufacturer, distributor, and procurement agency investing in AI innovation. Using wholesale price and cost-sharing contracts, they develop collaborative and coordinated solutions for a three-level AI-enabled healthcare supply chain, ensuring operational continuity.

2.6. Vaccine allocation

Optimal vaccine allocation can play a crucial role in managing shortages and significantly improving VSC performance. Henn (2020) performs an analysis of the allocation criteria pertaining to an anticipated scarcity of a forthcoming SARS-CoV-2 vaccine or other vaccines, along with the requisite measures for achieving worldwide immunity. Bennouna et al. (2022) introduce MIT-Cassandra, a novel machine-learning-based aggregation technique for forecasting cases and fatalities. Rey et al. (2023) look at decision-makers who must allocate vaccines with limited supplies to reduce their vulnerable populations. Muckstadt et al. (2023) develop a comprehensive objective function and a computationally efficient strategy for optimal vaccine allocation using a rolling-horizon approach in response to the pandemic. Their analysis demonstrates the impact of box size, dispensing site quantity, and capacity on system performance. Their findings indicate that the proposed vaccine allocation and distribution method would have accelerated immunization rates in the U.S. during the COVID-19 pandemic.

Given that our research focuses on VSC shortage issues, Table 1 summarizes relevant studies published after 2015 to contextualize our key contributions within the existing literature on VSC issues.

2.7. Research gaps and major contributions

Studies to date have focused on the causes of vaccine shortages and the use of empirical and mathematical models to address specific disease or epidemic circumstances. Moreover, prior research has predominantly concentrated on shortage issues within a specific domain of the supply chain network, specifically pertaining to end-users and producers. To the best of our knowledge, no comprehensive study exists that explores all aspects of factors contributing to shortages in the VSC, spanning from production through distribution and storage to final administration at health facilities. Furthermore, prior research did not provide solutions for improving VSC efficiency while considering vaccine shortages using a multi-criteria framework. Furthermore, there is a notable dearth of information on the viewpoints of managers who are responsible for overseeing VSC during periods of shortages and determining successful methods for deployment. Significantly, the COVID-19 pandemic has brought forth several novel elements that contribute to vaccine stockouts, including unprecedented global demand, interruptions in the supply chain, and intricate obstacles in distribution. To our knowledge, these VSC stockout elements before to and following COVID-19 are absent in any research frameworks within the extant literature on VSC in the Indian context. By addressing these deficiencies in the existing body of research, we can enhance the efficiency and efficacy of immunization programs, especially in areas with limited resources. This will eventually lead to improved public health outcomes. Moreover, these frameworks can be crucial for aiding policymakers in their decision-making processes, particularly in low- and middle-income countries where healthcare systems may be more susceptible to disruptions. Our study contributes the following knowledge to the existing body of operations management and VSC literature:

- Underline the importance of vaccine shortages in child immunization program performance of India, an aspect that is often overlooked by policymakers when formulating strategies in low- and middle-income countries.
- Demonstrate the causes of vaccine shortages and solutions to overcome shortages from production until vaccine administration using field surveys, literature review, and expert's opinions.
- Exhibit the function of MCDM framework, which ranks causes and solutions to assist VSC decision-makers in improving system performance.
- Insights on managerial perspectives for the management of VSC during shortages.

3. Methodology

The methodological approach of this study involves several key steps that are designed to address 3 key research questions. Initially, a comprehensive review of existing literature was conducted to identify the 10 causes of vaccine shortages and 12 potential solutions. This review provided a foundation for understanding the current state of VSC shortages and the challenges faced in managing shortages. Following the literature review, a field survey was conducted across 3 Indian states to gather primary data from experts and consumers (children parents and pregnant women) through interviews and discussions. These experts included doctors, immunization officers, procurement officers, cold chain managers, and other relevant stakeholders. This survey aimed to capture insights into the practical challenges and solutions from those directly involved in the VSC and the child immunization programs. Based on the collected data, an integrated framework combining the AHP and COPRAS-G was developed. This framework was used to systematically evaluate and rank the causes and solutions for vaccine shortages. To validate the stability of the results, a Monte Carlo simulation was performed using a uniform probability distribution in [0, 1]. This simulation helped ensure the robustness of the findings.

3.1. Grey system and fuzzy set theory

According to control theory, systems with both partially known and partially unknown information are classified as grey. The goal of incorporating Grey System Theory (GST) into our study serves a dual purpose. First, various distortions, biases, errors, and other imperfections often influence the evaluations and measurements made by decision-makers. While the decision-makers recognize some of these factors, others may remain unidentified or even impossible to determine. Thus, in practical scenarios, many systems continue to pose challenges in terms of analysis and exhibit unpredictable behavior due to limited data and inadequate information. Therefore, GST enables the modeling of such systems, which provides substantial benefits in terms of performance optimization. Second, GST aims to build theories, methods, concepts, and ideas for solving and analyzing complex and latent systems. When dealing with issues with a small sample size or insufficient information, GST can be a useful tool. With GST, systems operating in an unpredictable and partially known environment may quickly provide valuable and actionable feedback. This allows for accurate definition and effective monitoring of the system's functional activity (Javanmardi & Liu, 2019; Liu, Forrest, & Yang, 2012).

We also represent our problem with GST instead of Fuzzy Set Theory (FST). Grey theory addresses objective uncertainty, while FST addresses subjective uncertainty. Subjective uncertainty stems from a lack of knowledge, censorship, scientific ignorance, measurement errors, and the incapacity to confirm or observe, whereas objective uncertainty stems from the unpredictable nature of an environment. As a result, one of the characteristics of GST is the ability to construct models using small data sets. In contrast to FST, GST focuses on investigating entities that are capable of processing both explicit and implicit information. Therefore, our study framework reveals that GST is more suitable than FST (Khuman, 2021; Liu et al., 2012).

In GST, we select COPRAS-G from a variety of MCDM methodologies due to its complete logicalness and mathematical usefulness in processing incomplete system data, with the aim of enhancing performance and improving accuracy in the decision-making process. Furthermore, it is used to investigate the distinct alternatives and estimate the alternatives in line with their importance and degree of utility. The utility degree is represented as a percentage value. The percentage indicates the

Table 1
Summary of research papers on VSC issues published after 2015.

Source	Issues considered in VSC	Description	Methodologies Used
Hanson et al. (2017)	Real-time temperature regulation	All vaccines require strict and real-time temperature monitoring to maintain their quality and efficacy, as vaccinations are temperature-sensitive.	Data extraction through literature review.
Feddema et al. (2023)	The rate at which vaccines can be manufactured	To match demand, the rate of manufacturing capability needs to be prompt. Many times, a mismatch in production capacity causes shortages in VSC.	Two phase data collection: First is primary data collection and second is scoping literature review.
Li et al. (2022)	Production, transportation, and demand uncertainty	The literature reports mismatch of production capabilities, uncertainty in demand, and transportation challenges as prime causes of vaccine shortages.	Developed basic mathematical model for the scenario.
Hu et al. (2023)	Transparency in vaccinations, information sharing, real-time monitoring, and quality assurance	Vaccine transparency promotes access to information that could help detect poor quality and other specific issues such as counterfeit vaccines.	Built intelligent management system based on IoT, blockchain and machine learning.
Boeck et al. (2019)	Vaccine distribution and coverage	Vaccine distribution should be planned in such a way that it can effectively cover all required demand sites. Failing to establish an efficient distribution network is one of the causes of shortages.	Literature review using calculation method, analytical optimization and simulation.
Wang et al. (2023)	Logistics difficulties in VSC	Because the shelf life of vaccines is very short, low- and middle-income nations faces lots of logistics challenges to fulfill the demand at the right time and place.	Proposed two tailored column-and-constraint generation algorithms.
Gao et al. (2023)	VSC coordination and safety management	One of the biggest challenges in the safety management of vaccines, which directly affects public health, is the lack of coordination among all supply chain partners.	Proposed two dynamic game model
Lin et al. (2020)	Transportation decisions	Due to the sensitivity of vaccines to temperature changes, the retailer must verify a specific set of conditions during the delivery inspection process.	Developed the basic mathematical model for the scenario.
Sinha et al. (2023)	Infrastructure deficiency in VSC	Lack of infrastructure hampers the distribution system. VSC infrastructures include cold chain management systems and remote communication systems.	Developed model for demand forecasting and analyse inventory hedging strategies
Alam et al. (2021)	Lack of vaccine monitoring bodies	The authorized vaccine regulatory bodies are an effective way to deal with shortages at the country level.	Decision-Making Trial and Evaluation Laboratory (DEMATEL) method with Intuitionistic Fuzzy Sets (IFS)
Abbasi et al. (2023)	Waste in the VSC	There is wastage of vaccines due to expired shelf life or inappropriate temperature control.	Proposed Mixed-Integer Programming (MOMIP) problem with Multi-Objective Gray Wolf Optimizer (MOGWO) algorithm to address the developed model.
Chebolu-Subramanian & Sundarraj (2021)	Procurement process	The robust procurement process necessitates error-proof demand forecasting, which takes demand uncertainty into account.	Structured interview with normative modelling.
Asumah et al. (2023)	Uncertain yield	Uncertain yields often mismatch the vaccine requirements and supply, leading to shortages and waste in the VSC.	Letter to editor

degree of preference for one alternative over the set of existing alternatives. Other MCDM techniques no longer possess these features, which is why COPRAS-G has been successful in the decision-making process. COPRAS-G enables decision-makers to make more accurate decisions. Researchers accept COPRAS-G for its efficient management of uncertainty, subjectivity, and imprecise information (Maity et al., 2012; Zavadskas et al., 2010; Zolfani et al., 2012).

3.2. AHP and COPRAS-G

Decision-making is a cognitive process that requires the identification of the best course of action for the present set of alternatives and information. Making accurate and timely decisions is crucial, as it begins with accurately defining the problem and fixing the decision's objective. The next step involves gathering pertinent information and pinpointing the most practical solutions and alternatives (Chakraborty et al., 2023). The AHP method is highly regarded and widely used in decision-making problems. One major benefit of utilizing AHP is its capacity to handle subjective variables that are inherent in decision-making processes with hierarchical structures. AHP offers a high degree of flexibility and allows decision-makers to address inconsistencies, enabling them to incorporate subjectivity, work experience, and professional background. Aside from AHP, there are several other widely used MCDM methods, such as Viekriterijumsko Kompromisno Rangiranje (VIKOR), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and COPRAS-G. These approaches aim to determine the best alternative from a set of recognized alternatives by assigning them a score based on their level of importance. The COPRAS-G method, among other approaches, endeavors to compare alternatives and ascertain their relative importance in the presence of conflicts. Previous comparative assessments of VIKOR, TOPSIS, COPRAS-G, and other MCDM techniques have shown that COPRAS-G outperforms the others (Hezer et al., 2021; Podvezko, 2011; Rodrigues et al., 2014). For example, Hezer et al. (2021) research on the regional safety assessment for COVID-19 showed that COPRAS provides the most accurate results compared to VIKOR and TOPSIS. The COPRAS-G method independently calculates the maximized and minimized values of all criteria, eliminating the need for a typical sample distribution. As a result, existing literature supports the COPRAS-G method's effectiveness in alternative selection and evaluation (Nguyen et al., 2014).

COPRAS-G is selected to complement AHP by addressing the inherent uncertainties and incomplete information in the VSC. Furthermore, the Pythagorean fuzzy concept combined with AHP and COPRAS, known as PF-AHP and PF-COPRAS, is considered the state of the art for AHP and COPRAS-G methodology[1]. The research demonstrates that combining the AHP and COPRAS approaches in Pythagorean fuzzy set contexts might result in a more streamlined way of solving complicated problems, particularly when decision-makers become unclear regarding the allocation of preference to different issues. The combination offers a rational and effective approach to decision-making by addressing ambiguity through the utilization of crisp and fuzzy variants of MCDM techniques. Nevertheless, considering computational simplicity and satisfactory outcomes, previous studies have demonstrated that decision-making processes often employ the integration of AHP and COPRAS-G, excluding Pythagorean fuzzy as a significant instrument for decision-making. This integrated approach simplifies the handling and analysis of data, making it easier to make informed decisions (Buyukozkan & Gocer, 2021; Erdebilli et al., 2023). Therefore, the integration of AHP and COPRAS-G in our study, excluding the Pythagorean fuzzy provides a robust, transparent, and practical approach to identifying and prioritizing solutions for vaccine shortages. This combination ensures that the decision-making process is both systematic and practical to the challenges of the vaccine shortage.

4. The integrated framework

The integrated framework is depicted in Fig. 1. This paper addresses 3 key research questions—identifying the root causes of vaccine shortages in child immunization program of India, proposing solutions to mitigate these shortages, and demonstrating how a MCDM framework can enhance decision-making processes during shortages. To address these questions, relevant materials were gathered and an appropriate MCDM methodology was selected. Consequently, the integrated framework was divided into 4 phases, each elaborated upon in the subsequent subsections. Section 4.1 discusses phase 1's data gathering, including a literature review, field survey, and subject-matter expert input. Section 4.2 as phase 2 presents the usage of AHP process to determine the weighting of vaccine shortage causes. Section 4.3 of phase 3 of our framework describes the integrated AHP-COPRAS-G methodology utilization for solution ranking. Section 4.4 concludes with phase 4, a simulation to verify results robustness. A detailed explanation of each phase is given below.

4.1. Data collection

4.1.1. Document search

To collect relevant resources for the study, we began the process by conducting a comprehensive evaluation of the existing literature. Govindan & Hasanagic (2018) assert that scholars highly regard the Scopus bibliographic database as a valuable resource for accessing and analyzing extant literature, especially those published after 1995. For this reason, we eventually settled on Scopus as the primary repository for our collection of research and conference papers (from now on referred to as documents). The database was searched within document title, abstract, and keywords, using a combination of various keywords, including vaccine*, shortage*, stockout*, immuniz*, supply, chain*, child* to retrieve relevant documents. The study deemed only those English-language documents published from 2000 onwards suitable for inclusion. We analyzed the identified documents based on their title, abstract, and main body. After eliminating several duplicates, we ultimately selected a total of 78 documents for the study. Additionally, we gathered information from the International Federation of Pharmaceutical Manufacturers & Associations (IFPMA) expert discussion involving pharmaceutical industry representatives and immunization policymakers on the topic "From shortages to sustainable supply: How do we safeguard immunization progress and patient health?" The panel included the CEO of the International Pharmaceutical Federation, with expertise in global pharmacy and healthcare systems; a Senior Contracts Manager from UNICEF Supply Division, specializing in vaccine procurement and supply chain logistics; the Chief Quality Officer of Sanofi Pasteur representing IFPMA, focusing on vaccine quality and production; and a Technical Officer from the World Health Organization, with experience in vaccine pricing, supply, and procurement strategies. Together, they provided a comprehensive perspective on addressing vaccine shortages[2]. The document search procedure facilitated the identification of pertinent material for our study.

4.1.2. Field survey

In addition to the literature review method of data collection, this study incorporated a secondary instrument in the form of a field survey, as well as the insights and perspectives of experts in the field. The study commenced by identifying a group of 32 experts from 15 health facilities located in the Indian states of Uttarakhand, Uttar Pradesh, and Delhi.

[1] Appendix A provides a comprehensive explanation and steps for AHP and COPRAS-G.

[2] Geneva Pharma Forum on medicines and vaccines shortages 28 April 2017 – IFPMA; https://backslashcoding.com/work/old_ifpma/events-2/2017-geneva-pharma-forum-on-medicines-vaccines-shortages/.

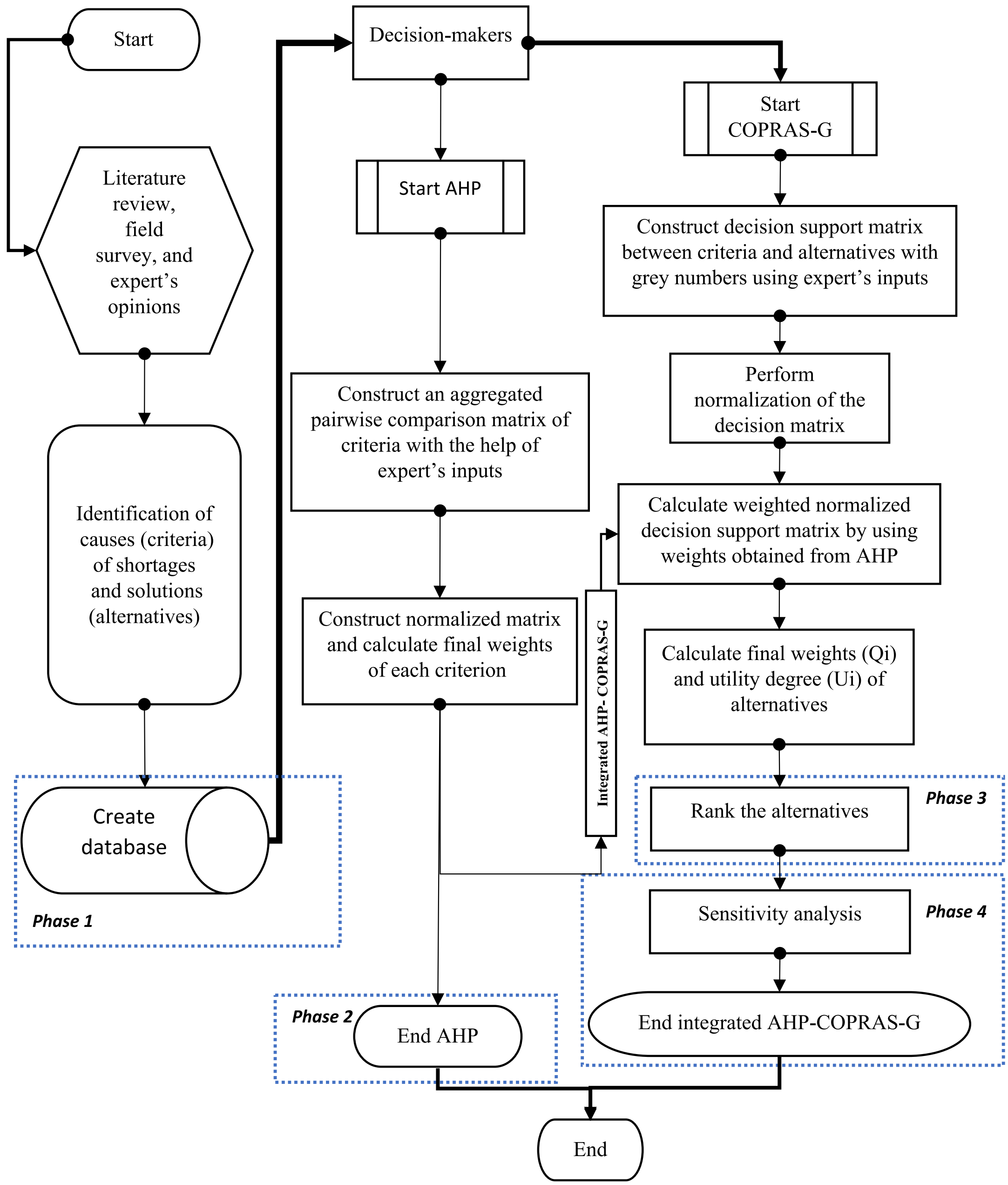

Fig. 1. Flowchart of the integrated framework.

However, after further discussion, 11 of the initially identified experts expressed their willingness to participate in the study by consenting to a 30-minute interview. The experts panel consist of doctors working with public health department, immunization officers, procurement officers, cold chain managers and other relevant stakeholders from the vaccine manufacturers and distributors. The group was diverse and cumulatively able to discuss all the related topics. Additionally, to gather data, we also conducted interviews with a sample of 32 customers residing in the districts of Dehradun, Haridwar, and Nainital in the state of Uttarakhand to understand perspectives on supply and end-user challenges. The selection of 32 experts (and final interview with 11) and 32 customers was guided by the principle of saturation and the need for balanced representation, ensuring that both technical supply chain perspectives (experts) and end-user experiences (customers) were captured to comprehensively address vaccine shortages. The study of Hennink and Kaiser (2022) on principle of saturation shows that interview of more than 9 experts are sufficient. Also, Hora et al., (2023) followed the principles of saturation and selected 11 key experts to conduct study on vaccines.

We used semi structured interviews and asked experts about the factors contributing to vaccine shortages in child immunization programs, as well as the primary strategies for mitigating shortages and enhancing delivery efficiency throughout the entire supply chain. For instance, we asked experts, “What happens if there is a district level shortage?” “What are the main reasons for shortages at the central level?” “How do consumers react when vaccines are not available in health facilities?” and so forth. Similarly, we asked consumers, “When vaccines are not available at the health facilities, do you still come at the stipulated time to receive your left-over dose?” “Does the immunization program notify you if vaccines are available before your appointment or before your follow-up visit in case there is a stockout?” “Do you go to the private health facility if the government immunization facility is out of stock?” and so forth. Microsoft Excel 16.0 compiled all the information from the survey and literature review, ultimately selecting 10 causes and

12 solutions for the study, as presented in Tables 2 and 3.

4.2. Criteria's weight calculations using AHP

The same group of 11 VSC experts then received a first questionnaire. In the questionnaire the objective was to determine the relative importance of the criteria using pairwise comparison. The questionnaire encompassed the following questions: "To what extent does the criterion of 'production (C1)' outweigh the criterion of 'regulation (C2)' in terms of assigning importance to the primary factors contributing to vaccine shortages?" The expert opinions were then recorded using Saaty's 9-point scale of "Equally important (EI)", "Moderately important (MI)", "Strongly important (SI)", "Extremely important (EXI)", and "Extremely more important (EXMI), as presented in Table 4. Based on the answers to the questionnaire, we used Equations A(1)–A(2) to make a final pairwise comparison matrix between the criteria, which can be seen in Table 5. The consistency ratio for the matrix was 0.0887 (using Eqs. A(3)–A(4), which is less than 0.1 and acceptable. Finally, in Table 6, we derived the normalized matrix and priority weight using Eq. A(5).

4.3. Ranking alternatives using AHP-COPRS-G

We supplied the same experts with a second questionnaire to assess the relevance of the alternatives. The sample question was, "How important is the effect of the alternative 'better information system (A1)' to overcome the vaccine shortage caused by 'production (C1)'?" The experts' linguistic variable responses were converted into grey numbers using the scale presented in Table 7. Next, we constructed a decision support matrix using expert insights and grey numbers, as shown in Table 8. We then constructed the normalized decision support matrix using Eqs. A(7)–A(9) of the COPRAS-G technique, as shown in Table 9. Next, we created a weighted normalized decision matrix, as depicted in Table 10, by utilizing the weights of each criterion obtained from AHP and using Eqs. A10–A12. Finally, we calculated the final ranking of alternatives using Eqs. A13–A18, as presented in Table 11.

4.4. Sensitivity analysis

A sensitivity analysis is carried out to assess the robustness of the AHP-COPRAS-G technique. We employ Monte Carlo simulation to sample variants of each cause and solution. This computational method utilizes random sampling to approximate numerical results, facilitating precise decision-making amidst ambiguity. Monte Carlo simulation is especially useful in situations with few empirical data or significant unpredictability, as it assesses complicated system behavior by examining outcomes from several randomly created scenarios. This method enables the evaluation of variation and anticipated values of causes and solutions indicators that influence the VSC shortages. Furthermore, it discerns probabilistic patterns and risk thresholds, with outcomes frequently approaching normal distributions when adequately large samples are employed. These insights are essential for strategizing and modifying supply chain operations amid unpredictable demand and supply circumstances (Guitouni et al., 2025). For this purpose, a Monte Carlo simulation with uniform probability distribution is performed in the domain of [0, 1]. The simulation involves generating criterion weights randomly and repeating the process 150 times, ensuring that the criteria weight satisfies the condition $0 \leq w_j \leq 1$; $\sum_{i=1}^{n} w_j = 1$. Following the simulation, Saaty & Ergu (2015) indicate that the qualitative criterion for assessing robustness is the attainment of a "less variation in final rankings of the factors" or "consistent ranking". Fig. 2 displays the simulation outcomes for alternative weights Q_i across 150 cases. The findings indicate that modifying the input weight q_i has led to alterations in the weights of the alternatives Q_i; however, the ultimate results have not exhibited significant variations. Notably, alternatives A12, A3, and A5 consistently occupy the highest rank in maximum

Table 2
List of shortage causes and their descriptions.

Cause	Denotation	Description	Reference
Production	C1	Due to significant set up costs, technological, and knowledge requirements, there are limited vaccine producers globally. One of the main reasons of vaccine shortages is that vaccine producers cannot produce enough vaccines to fulfill globally demand for national vaccination programs.	(Chandra & Kumar, 2018; B. Li et al., 2022; Lydon et al., 2008; Mamani et al., 2013) & Experts Suggestions
Regulatory complexities	C2	To acquire vaccines for use in national immunization programs, India's vaccine regulatory procedures are extremely complex. Such regulatory issues make it difficult for vaccine manufacturers and immunization programs to supply and acquire vaccines, resulting in vaccine shortages.	(Gupta et al., 2013; Lydon et al., 2017)
Procurement system	C3	The occurrence of vaccine shortages at various levels of VSC in many developing nations is often attributed to inflexible procurement mechanisms coupled with delays in purchase orders.	(Amarasinghe & Mahoney, 2011; Lydon et al., 2017; PATH et al., 2015) & Experts Suggestions
Product and packaging requirements	C4	Immunization programs in India procure vaccines from Indian manufacturers, while the WHO and UNICEF also provide vaccines to them at free of cost. Now these manufacturing industries, together with WHO and UNICEF, give vaccines to various countries, resulting in differing product and packaging needs. This product diversity contributes to supply and demand uncertainty, which can lead to shortages.	(Klein & Myers, 2006; Lydon et al., 2017)
Uncertainty in demand	C5	Due to various internal and external factors, it becomes difficult to forecast the actual demand for each type of vaccine to be required in use	(Chick et al., 2008, 2017; Dai et al., 2016; Mamani et al., 2013; Yan, 2023) & Experts Suggestions

(continued on next page)

Table 2 (*continued*)

Cause	Denotation	Description	Reference
		in national immunization programs.	
Vaccine wastages	C6	Due to various factors such as cold chain failures, expiry, breakage, poor handling, etc. the vaccines do not reach to the health centers and causes vaccine shortages.	(Guichard et al., 2010; Setia et al., 2002; Shreyash, Pradeep, Prakash, & Bansal, 2013; Ministry of Health and Family Welfare, 2010) & Experts Suggestions
Political commitment and financing	C7	Immunization programs do not receive enough funding due to political indifference. This delays vaccine purchase orders, causing temporary shortages in the supply chain.	(Chandra & Kumar, 2021; Gandhi et al., 2013; Lydon et al., 2014)
Changes in immunization program schedules	C8	Each nation has its own immunization program schedule, which varies from time to time. This transformation frequently results in a scarcity of certain vaccines that are required in an emergency.	(Gupta et al., 2013) & Experts Suggestions
Improper stock management and poor coordination within the supply chain	C9	Vaccine shortages often happens as a result of poor stock management and inadequate coordination between each element of the supply chain.	(Chandra & Vipin, 2021; Chick et al., 2017; Gao et al., 2023) & Experts Suggestions
Information gap about vaccines at risk of shortages	C10	Due to lack of information on current and future supply capacity of manufacturers, lack of technological development, and no authorized authority frame to report vaccine shortages, there is often an information gap between the supplier and the buyer regarding vaccines at risk of shortage. Thus, information gaps produce shortages in most countries.	(IFPMA, 2017; Jie & Jianpei, 2015; Z. Li et al., 2018; A. K. Yadav et al., 2023; P. Yadav et al., 2014; Zaffran et al., 2013)

cases. The Monte Carlo simulation results are important in our study because in the absence of validation through comparison with other MCDM techniques, the results depicted in Fig. 2 indicate that the ranking of alternatives is unlikely to vary significantly, even if different MCDM methods are employed. This conclusion is based on our simulation, which generated 150 scenarios to modify the input weights; these weights ultimately reflect the results of a MCDM approach like AHP. The results are therefore crucial for VSC decision-makers, indicating that A12, A3, and A5 are significant determinants regardless of the evaluation technique employed. The graphical representation in Fig. 3

Table 3
List of solutions and their descriptions.

Solution	Denotation	Description	Reference
Better information system	A1	Implementing a robust information system to document and communicate shortages, their severity, and improve information sharing will help address shortage issues in the VSC.	(Chandra & Kumar, 2021; Lydon et al., 2017; Manupati et al., 2021; Negandhi et al., 2016) & Experts Suggestions
Analyzing the risk of non-production	A2	Vaccine manufacturers must assess the risk of non-production. Manufacturers must classify vaccines as vital items to assure their supply. If a manufacturer cannot produce vaccines, the country must collaborate to help.	(IFPMA, 2017) & Experts Suggestions
High-quality active procurement process	A3	It is crucial to reinforce the procurement process to facilitate high-quality procurement that can strengthen immunization programs, not just in terms of higher quality vaccines but also by ensuring a consistent supply.	(IFPMA, 2017) & Experts Suggestions
Removing all the regulatory barriers	A4	Due to the regulatory complexities of each country, it is highly important that certain regulatory barriers be eliminated to make it easier for vaccine manufacturers to ship vaccines to any country.	(Gupta et al., 2013; Lydon et al., 2017; Shrivastava et al., 2012)
Authorized body in charge of shortage issues	A5	As each nation has an official body for child immunization programs, it is also important that governments have an officially approved body for vaccine shortage with which all communication regarding vaccine shortages can take place.	(IFPMA, 2017) & Experts Suggestions
Better demand forecasting	A6	To satisfy the essential needs of the vaccination programs, manufacturers and VSC decision-makers should develop a better demand forecasting mechanism.	(Adida et al., 2013; Center for Global Development, 2007; R. K. Chiu et al., 2007, 2008; R.-K. Chiu & Kuo, 2006; Kamara et al., 2008; Lydon et al., 2017) & Experts Suggestions

(*continued on next page*)

Table 3 (*continued*)

Solution	Denotation	Description	Reference
Introduction of new technologies and new platforms	A7	Many developing nations, including India, still lack well-equipped technology to sustain vaccination programs in the event of a shortage. To deal with such shortages and design sustainable vaccination programs, better technology and new platforms for information sharing, demand forecasting, cold chain equipment, vaccine storage must be developed in the future.	(Negandhi et al., 2016; A. K. Yadav et al., 2023; P. Yadav et al., 2014; Zaffran et al., 2013) & Experts Suggestions
The industry should be transparent in notifying of shortages	A8	It is imperative that vaccine producers maintain transparency concerning shortages, enabling governments to adequately prepare in advance to address these shortages.	(IFPMA, 2017) & Experts Suggestions
Incentivize more manufacturers to enter into the specific vaccine supply market	A9	The government should provide support to pharmaceutical companies to facilitate the production of vaccines, especially life-saving vaccines to meet the global demand.	(Bennouna et al., 2022; Chandra & Vipin, 2021; Dai et al., 2016; Mamani et al., 2013)
Constructing technology infrastructure at various levels of supply chains for buffer stocks	A10	Building technology infrastructure at various levels of supply chains for buffer stocks and VSC management can help stock more vaccines that can be utilized in the event of a shortage.	(Jahani et al., 2022; Rai et al., 2022; Shweta & Kumar, 2021; A. K. Yadav et al., 2023) & Experts Suggestions
Incorporate supply chain experts, stakeholders, government organization, healthcare professionals, pharmacists, etc. to work together	A11	Collaborative information and knowledge exchange among diverse stakeholders, such as supply chain experts, government organizations, healthcare professionals, pharmacists, and other relevant VSC members, can effectively manage shortages in the VSC.	(IFPMA, 2017) & Experts Suggestions
Better monitoring system to measure shortages	A12	Vaccine stocks should be evaluated on a regular basis, and if a shortfall is anticipated to arise at any stage of the supply chain or in the future, it should be immediately notified to the appropriate authorities, for instance, the solution proposed in A5.	(IFPMA, 2017; Ng et al., 2018) & Experts Suggestions

Table 4
Scale used for pairwise comparison.

AHP – Saaty's 9 Point scale	
1	Equally important (EI)
3	Moderately important (MI)
5	Strongly important (SI)
7	Extremely important (EXI)
9	Extremely more important (EXMI)
2,4,6,8	Intermediate values
	Reciprocals are used for inverse comparison

illustrates the ranking of alternatives. In conclusion, the integrated model yields consistent and reliable results.

5. Results

Fig. 4 illustrates the outcome of our integrated model. The findings indicate that the hierarchy of causes of vaccine shortages, as determined by their respective weights, is as follows—C5 holds the highest priority, followed by C9, C2, C6, C1, C7, C8, C10, C3, and C4. This suggests that uncertainty in demand, improper stock management and poor coordination within the supply chain, and regulatory complexities are the three primary criteria causing vaccine shortages. The three criteria at the top of our study's list of vaccine shortages might be linked to the fact that VSCs in India continue to use an outmoded forecasting technique that overlooks demand and supply unpredictability, resulting in shortages. Similarly, improper stock management and poor coordination issues are common in VSCs in India because primary healthcare system managers, particularly located at lower levels of the supply chain such as primary health centers, hospitals, and community health centers, fail to identify the best inventory control and coordination strategy to manage shortages and waste. Regulatory issues are a plausible outcome, as pharmaceutical industries are vulnerable to external and internal uncertainties induced by government and WHO regulatory policies. Other causes include wastages of vaccine (C6) caused by issues such as cold chain problems, expiration, and improper handling, as well as a global scarcity of vaccine producers (C1), which ultimately leads to a vaccine shortage.

Based on the results presented in Fig. 5, the order of importance for the alternatives is as follows—A12 is the top choice, with A3, A5, A11, A10, A4, A1, A9, A8, A2, A7, and A6 following in that order. Mahmud et al. (2023) states that the most efficacious solutions for mitigating vaccine shortages in developing countries involve the implementation of a system to identify, monitor, and report shortages to all the decision-makers of a supply chain. Similar to Mahmud et al. (2023), our study also identifies that an improved monitoring system to measure shortages (A12) can be crucial strategy to manage the risk associated with shortages and other issues in VSC. In addition, we highlight that a high-quality active procurement process (A3), and a collaborative approach by all stakeholders involved in the VSC (A5) are also imperative solutions to manage shortages. The acquisition procedure for vaccines is a critical problem that poses a significant challenge in the VSC, as highlighted by several studies (Filia et al., 2022). Other possible solutions include incorporating supply chain experts, stakeholders, government

Table 5
Pairwise comparison matrix for the criteria.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1.000	0.376	2.968	3.937	0.312	0.339	2.940	0.361	0.576	5.868
C2	2.657	1.000	6.838	4.850	0.499	1.977	3.926	2.945	0.555	4.864
C3	0.337	0.146	1.000	3.003	0.177	0.249	0.288	0.380	0.244	0.591
C4	0.254	0.206	0.333	1.000	0.178	0.244	0.232	0.307	0.135	0.344
C5	3.207	2.003	5.665	5.615	1.000	2.945	2.955	3.949	2.956	4.830
C6	2.950	0.506	4.011	4.102	0.340	1.000	0.380	2.961	0.348	1.979
C7	0.340	0.255	3.472	4.302	0.338	2.629	1.000	1.977	0.320	2.966
C8	2.770	0.340	2.629	3.260	0.253	0.338	0.506	1.000	0.348	1.978
C9	1.736	1.801	4.093	7.430	0.338	2.874	3.124	2.874	1.000	5.801
C10	0.170	0.206	1.691	2.905	0.207	0.505	0.337	0.506	0.172	1.000

λ_{max} = ***11.1899, CI = 0.1322, RI = 1.49, CR = 0.0887;CR ≤ 0.1 consistency***

Table 6
Normalized matrix and final priority weights.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Weight (q_j)
C1	0.065	0.055	0.091	0.097	0.086	0.026	0.187	0.021	0.087	0.194	**0.091**
C2	0.172	0.146	0.209	0.120	0.137	0.151	0.250	0.171	0.083	0.161	**0.160**
C3	0.022	0.021	0.031	0.074	0.048	0.019	0.018	0.022	0.037	0.020	**0.031**
C4	0.016	0.030	0.010	0.025	0.049	0.019	0.015	0.018	0.020	0.011	**0.021**
C5	0.208	0.293	0.173	0.139	0.275	0.225	0.188	0.229	0.444	0.160	**0.233**
C6	0.191	0.074	0.123	0.102	0.093	0.076	0.024	0.172	0.052	0.065	**0.097**
C7	0.022	0.037	0.106	0.106	0.093	0.201	0.064	0.115	0.048	0.098	**0.089**
C8	0.180	0.050	0.080	0.081	0.070	0.026	0.032	0.058	0.052	0.065	**0.069**
C9	0.113	0.263	0.125	0.184	0.093	0.219	0.199	0.167	0.150	0.192	**0.171**
C10	0.011	0.030	0.052	0.072	0.057	0.039	0.021	0.029	0.026	0.033	**0.037**

Table 7
Linguistic variables and grey numbers for alternative assessment (Nguyen et al., 2014).

Linguistic variables	Grey numbers
Very poor	[1,2]
Poor	[2,4]
Fair	[4,6]
Good	[6,8]
Very Good	[8,9]

organizations, healthcare professionals, pharmacists, etc. to work together (A11) and constructing technology infrastructure at various levels of supply chains for buffer stocks (A10).

6. Discussion

This paper examines the VSC of child immunization program of India to address vaccine shortages. Ten primary causes, derived from literature, field surveys, and expert opinions, address our first research question, helping decision-makers identify the core problems for vaccine shortages. Twelve proposed solutions address our second research question, helping policymakers develop effective strategies. Finally, an integrated AHP-COPRAS-G multi-criteria framework prioritizes these solutions based on their impact, answering our third research question. The results are validated through sensitivity analysis.

We show that the uncertainty surrounding demand, with a weight of 0.233, is the primary factor causing vaccine shortages. Extensive scholarly investigation and expert evaluation have consistently emphasized the significant challenge that vaccine demand poses for child vaccination programs in India (Chiu & Kuo, 2006; Kaufmann et al., 2011; Sekhri, 2006). Our findings are consistent with Kaufmann et al. (2011), where we emphasize the role of demand forecasting in managing shortages. Accurate predictions are essential to ensure that vaccine supplies meet the needs of the population. However, there are notable differences between our study and Kaufmann. We employ a MCDM framework to rank causes and solutions of vaccine shortages, offering a structured way for decision-makers to prioritize actions. In contrast, Kaufmann et al. (2011) provide a broad analysis based on expert opinions, drawing on their extensive experience and

Table 8
The decision support matrix for alternatives with grey numbers.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Optimal	Max	Min	Max	Min	Min	Min	Max	Min	Max	Max
q_j	0.091	0.160	0.031	0.021	0.233	0.097	0.089	0.069	0.171	0.037
A1	[6,8]	[4,6]	[8,9]	[8,9]	[8,9]	[4,6]	[4,6]	[8,9]	[6,8]	[8,9]
A2	[4,6]	[4,6]	[6,8]	[4,6]	[4,6]	[6,8]	[4,6]	[8,9]	[4,6]	[4,6]
A3	[6,8]	[4,6]	[6,8]	[1,2]	[4,6]	[4,6]	[6,8]	[6,8]	[4,6]	[4,6]
A4	[8,9]	[8,9]	[8,9]	[4,6]	[6,8]	[6,8]	[4,6]	[4,6]	[8,9]	[6,8]
A5	[4,6]	[4,6]	[6,8]	[2,4]	[6,8]	[4,6]	[4,6]	[6,8]	[6,8]	[8,9]
A6	[4,6]	[2,4]	[2,4]	[4,6]	[8,9]	[8,9]	[4,6]	[8,9]	[4,6]	[8,9]
A7	[8,9]	[4,6]	[4,6]	[8,9]	[8,9]	[8,9]	[4,6]	[6,8]	[6,8]	[6,8]
A8	[4,6]	[2,4]	[2,4]	[2,4]	[8,9]	[4,6]	[4,6]	[6,8]	[4,6]	[8,9]
A9	[8,9]	[2,4]	[2,4]	[6,8]	[8,9]	[4,6]	[4,6]	[8,9]	[4,6]	[6,8]
A10	[8,9]	[4,6]	[8,9]	[6,8]	[8,9]	[8,9]	[4,6]	[8,9]	[8,9]	[8,9]
A11	[8,9]	[8,9]	[8,9]	[6,8]	[6,8]	[4,6]	[8,9]	[8,9]	[6,8]	[6,8]
A12	[2,4]	[2,4]	[8,9]	[4,6]	[2,4]	[4,6]	[4,6]	[4,6]	[2,4]	[2,4]

Table 9
The normalized decision-making matrix.

	C1		C2		C3		C4		C5		C6		C7		C8		C9		C10	
A1	0.0755	0.1006	0.0678	0.1017	0.1032	0.1161	0.1221	0.1374	0.0941	0.1059	0.0537	0.0805	0.0611	0.0916	0.0899	0.1011	0.0822	0.1096	0.0958	0.1078
A2	0.0503	0.0755	0.0678	0.1017	0.0774	0.1032	0.0611	0.0916	0.0471	0.0706	0.0805	0.1074	0.0611	0.0916	0.0899	0.1011	0.0548	0.0822	0.0479	0.0719
A3	0.0755	0.1006	0.0678	0.1017	0.0774	0.1032	0.0153	0.0305	0.0471	0.0706	0.0537	0.0805	0.0916	0.1221	0.0674	0.0899	0.0548	0.0822	0.0479	0.0719
A4	0.1006	0.1132	0.1356	0.1525	0.1032	0.1161	0.0611	0.0916	0.0706	0.0941	0.0805	0.1074	0.0611	0.0916	0.0449	0.0674	0.1096	0.1233	0.0719	0.0958
A5	0.0503	0.0755	0.0678	0.1017	0.0774	0.1032	0.0305	0.0611	0.0706	0.0941	0.0537	0.0805	0.0611	0.0916	0.0674	0.0899	0.0822	0.1096	0.0958	0.1078
A6	0.0503	0.0755	0.0339	0.0678	0.0258	0.0516	0.0611	0.0916	0.0941	0.1059	0.1074	0.1208	0.0611	0.0916	0.0899	0.1011	0.0548	0.0822	0.0958	0.1078
A7	0.1006	0.1132	0.0678	0.1017	0.0516	0.0774	0.1221	0.1374	0.0941	0.1059	0.1074	0.1208	0.0611	0.0916	0.0674	0.0899	0.0822	0.1096	0.0719	0.0958
A8	0.0503	0.0755	0.0339	0.0678	0.0258	0.0516	0.0305	0.0611	0.0941	0.1059	0.0537	0.0805	0.0611	0.0916	0.0674	0.0899	0.0548	0.0822	0.0958	0.1078
A9	0.1006	0.1132	0.0339	0.0678	0.0258	0.0516	0.0916	0.1221	0.0941	0.1059	0.0537	0.0805	0.0611	0.0916	0.0899	0.1011	0.0548	0.0822	0.0719	0.0958
A10	0.1006	0.1132	0.0678	0.1017	0.1032	0.1161	0.0916	0.1221	0.0941	0.1059	0.1074	0.1208	0.0611	0.0916	0.0899	0.1011	0.1096	0.1233	0.0958	0.1078
A11	0.1006	0.1132	0.1356	0.1525	0.1032	0.1161	0.0916	0.1221	0.0706	0.0941	0.0537	0.0805	0.1221	0.1374	0.0899	0.1011	0.0822	0.1096	0.0719	0.0958
A12	0.0252	0.0503	0.0339	0.0678	0.1032	0.1161	0.0611	0.0916	0.0235	0.0471	0.0537	0.0805	0.0611	0.0916	0.0449	0.0674	0.0274	0.0548	0.0240	0.0479

Table 10
The weighted normalized decision support matrix for the alternatives.

	C1		C2		C3		C4		C5		C6		C7		C8		C9		C10	
A1	0.0069	0.0091	0.0109	0.0163	0.0032	0.0036	0.0026	0.0029	0.0220	0.0247	0.0052	0.0078	0.0054	0.0082	0.0062	0.0070	0.0140	0.0187	0.0035	0.0040
A2	0.0046	0.0069	0.0109	0.0163	0.0024	0.0032	0.0013	0.0020	0.0110	0.0165	0.0078	0.0104	0.0054	0.0082	0.0062	0.0070	0.0093	0.0140	0.0018	0.0027
A3	0.0069	0.0091	0.0109	0.0163	0.0024	0.0032	0.0003	0.0007	0.0110	0.0165	0.0052	0.0078	0.0082	0.0109	0.0047	0.0062	0.0093	0.0140	0.0018	0.0027
A4	0.0091	0.0103	0.0217	0.0244	0.0032	0.0036	0.0013	0.0020	0.0165	0.0220	0.0078	0.0104	0.0054	0.0082	0.0031	0.0047	0.0187	0.0210	0.0027	0.0035
A5	0.0046	0.0069	0.0109	0.0163	0.0024	0.0032	0.0007	0.0013	0.0165	0.0220	0.0052	0.0078	0.0054	0.0082	0.0047	0.0062	0.0140	0.0187	0.0035	0.0040
A6	0.0046	0.0069	0.0054	0.0109	0.0008	0.0016	0.0013	0.0020	0.0220	0.0247	0.0104	0.0117	0.0054	0.0082	0.0062	0.0070	0.0093	0.0140	0.0035	0.0040
A7	0.0091	0.0103	0.0109	0.0163	0.0016	0.0024	0.0026	0.0029	0.0220	0.0247	0.0104	0.0117	0.0054	0.0082	0.0047	0.0062	0.0140	0.0187	0.0027	0.0035
A8	0.0046	0.0069	0.0054	0.0109	0.0008	0.0016	0.0007	0.0013	0.0220	0.0247	0.0052	0.0078	0.0054	0.0082	0.0047	0.0062	0.0093	0.0140	0.0035	0.0040
A9	0.0091	0.0103	0.0054	0.0109	0.0008	0.0016	0.0020	0.0026	0.0220	0.0247	0.0052	0.0078	0.0054	0.0082	0.0062	0.0070	0.0093	0.0140	0.0027	0.0035
A10	0.0091	0.0103	0.0109	0.0163	0.0032	0.0036	0.0020	0.0026	0.0220	0.0247	0.0104	0.0117	0.0054	0.0082	0.0062	0.0070	0.0187	0.0210	0.0035	0.0040
A11	0.0091	0.0103	0.0217	0.0244	0.0032	0.0036	0.0020	0.0026	0.0165	0.0220	0.0052	0.0078	0.0109	0.0122	0.0062	0.0070	0.0140	0.0187	0.0027	0.0035
A12	0.0023	0.0046	0.0054	0.0109	0.0032	0.0036	0.0013	0.0020	0.0055	0.0110	0.0052	0.0078	0.0054	0.0082	0.0031	0.0047	0.0047	0.0093	0.0009	0.0018

Table 11
Utility value of the alternatives with their final ranking.

	P_i	R_i	Q_i	U_i	Final rank
A1	0.0383	0.0528	0.0811	**79.94%**	**7**
A2	0.0292	0.0447	0.0798	**78.63%**	**10**
A3	0.0342	0.0398	0.0911	**89.73%**	**2**
A4	0.0429	0.0569	0.0826	**81.37%**	**6**
A5	0.0354	0.0457	0.0849	**83.61%**	**3**
A6	0.0292	0.0508	0.0736	**72.55%**	**12**
A7	0.0380	0.0562	0.0782	**77.03%**	**11**
A8	0.0292	0.0444	0.0800	**78.85%**	**9**
A9	0.0325	0.0469	0.0807	**79.50%**	**8**
A10	0.0436	0.0569	0.0833	**82.05%**	**5**
A11	0.0441	0.0577	0.0833	**82.08%**	**4**
A12	0.0220	0.0284	0.1015	**100.00%**	**1**

P_i = weighted mean normalize sum (maximization type); Q_i= weight/ relative significance.
R_i = weighted mean normalize sum (minimization type); U_i= utility degree.

consultations with global health organizations. Kaufmann et al. (2011) discuss a range of strategies and recommendations, including improving coordination between vaccine donors and host-country officials, better training for supply-chain managers, and exploring new vaccine and logistics technologies. Additionally, our study specifically addresses vaccine shortages in child immunization program India, providing targeted solutions for the Universal Immunization Program (UIP) India unique challenges. The UIP in India encounters several challenges stemming from its enormous activities, resulting in an inherent uncertainty regarding the demand for vaccines. The disparity between demand and supply often leads to a situation where manufacturers and UIP India produce and buy a quantity that is either inadequate to fulfill the demand or excessively large, resulting in wastage. Therefore, a better monitoring system to measure shortages may serve as an effective strategy for addressing demand-related challenges and other issues. This implies that instead of focusing on better demand forecasting (A6) and putting in place new technologies and platforms (A7), it would be better to set up a strong monitoring system to measure shortages (A12) and get supply chain experts, stakeholders, government agencies, healthcare professionals, pharmacists, and others to work together (A11) as ways to improve system performance. An authorized body in charge of shortage issues might regularly evaluate vaccine inventory, creating a mechanism to assess vaccine shortages (A5) and further improve the overall performance. In this context, Schnepf (2022) and Lydon et al. (2017) points that a key driver of demand uncertainty and resultant vaccine shortages is public vaccination hesitancy. While we concur with Lydon et al. (2017) that vaccine hesitancy is the primary factor influencing demand uncertainty, their analysis emphasizes a global perspective. We contend that while vaccine hesitancy significantly contributes to demand uncertainty, parents in India have become increasingly cognizant of the need of vaccination in recent years within the child immunization program. They typically do not differentiate between public and private immunization services for their children. The problem of vaccine hesitancy has begun to diminish; however, consumers frequently fail to attend their scheduled or future vaccinations visits due to factors such as neglecting their vaccination scheduled information from the UIP, no proper notification about vaccine stockouts from UIP to consumers that results in future trust issues, and various personal and professional issues. Therefore, we recommend solutions such as establishing an authorized agency responsible for addressing shortages to inform consumers promptly. This real-time vaccine stock monitoring system providing parents with up-to-date stock availability information can foster greater trust in immunization programs. Policymakers can recommend this approach to mitigate shortages and enhance the overall performance of the UIP. According to some VSC experts, a centralized information system that is robust in nature may prove to be more advantageous in the Indian context. This system would allow decision-makers to monitor and report the demand for each region or country to manufacturers, thereby facilitating better demand forecasting. Different state and district levels can also employ this methodology to obtain more accurate information regarding vaccine shortages. Liu et al. (2023) assert that a centralized system, such as blockchain implementation in vaccination programs, can be a pivotal strategy for information sharing and coordinating the VSC, potentially reducing the risk of shortages for supply chain members. A crucial measure to contemplate could be the implementation of a high-quality active procurement process. Our findings align with Liu and Lou (2022) study that emphasis on strategic prioritization and efficient vaccine distribution. While Liu and Lou (2022) use mathematical models to optimize COVID-19 vaccine allocation during vaccine shortages, our work focuses on identifying and ranking specific causes and solutions to mitigate vaccine shortages in the child immunization program in India. Both studies highlight the importance of prioritizing certain groups and improving monitoring systems to ensure effective vaccine management. Our approach, like Liu

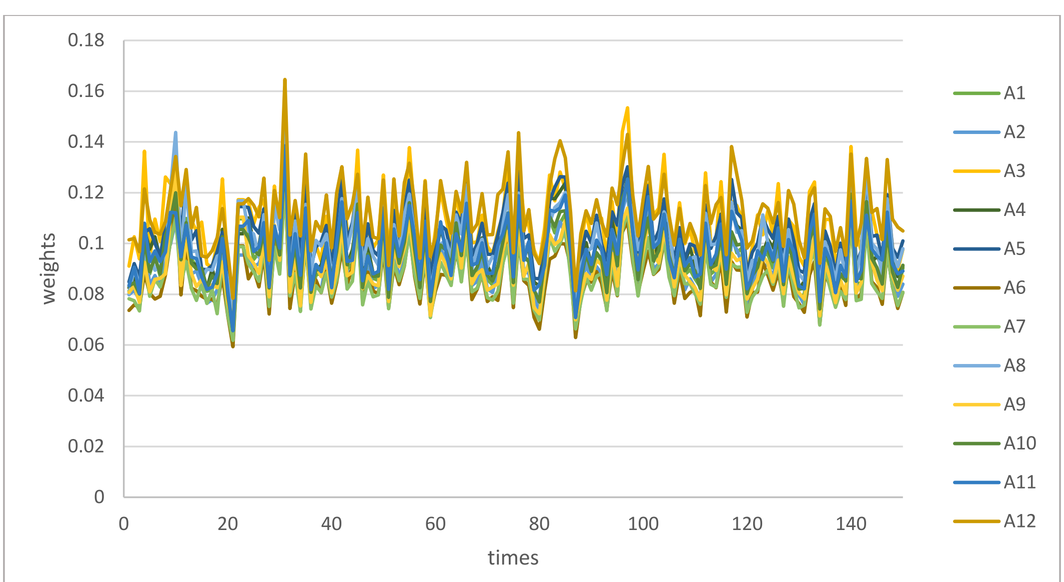

Fig. 2. Weights of twelve alternatives in one hundred fifty times simulation.

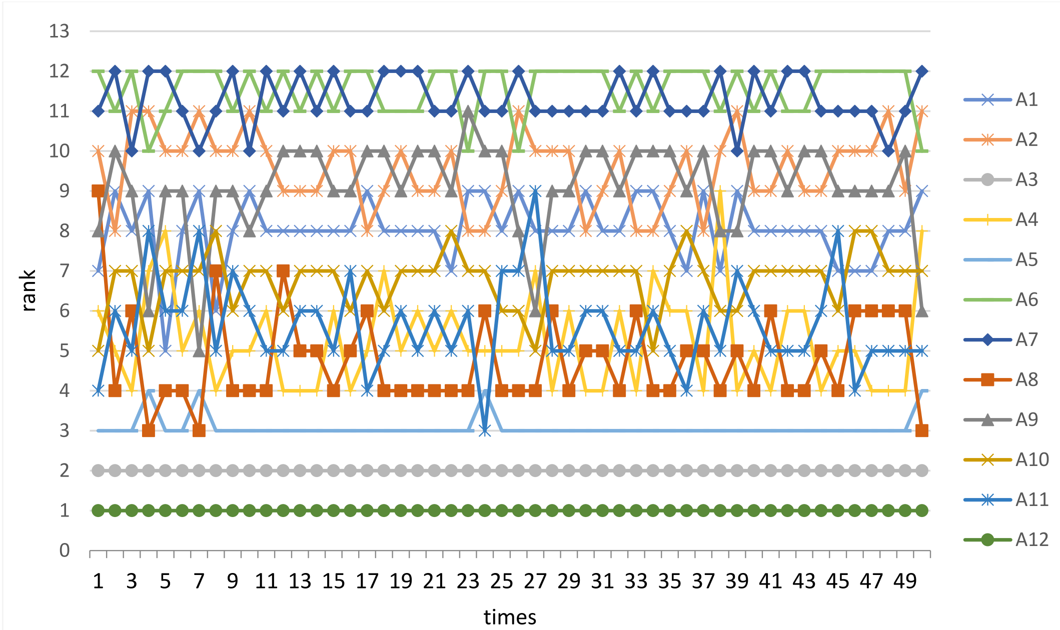

Fig. 3. Ranking of alternatives.

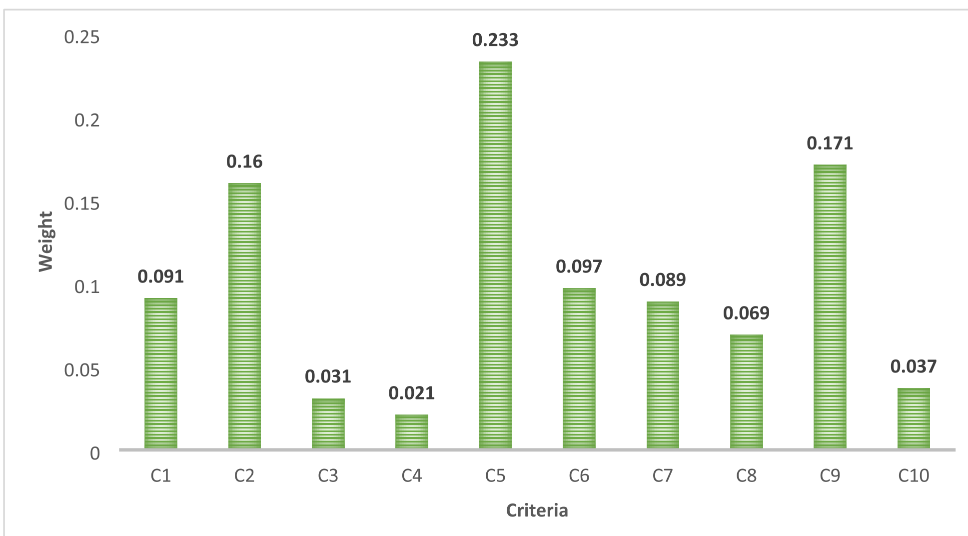

Fig. 4. Weight of ten criteria for vaccine shortages.

and Lou (2022), aims to provide decision-makers with tools to enhance immunization programs, albeit through different methodologies and focus areas. Both works underscore the need for strategic planning and informed decision-making from the centralized authorities to address vaccine shortages and improve public health outcomes.

Established approximately three decades ago, the immunization program in India has persisted with the same strategy to this day. However, today, the requirements and anticipations of parents who bring their children for vaccination have seen notable transformations, demanding a commensurate adjustment of the procurement methods of immunization programs to improve the accessibility of their vaccine inventory. To improve the procurement process, it is imperative that UIP India place equal emphasis on both the quality of the procured product and the sustainability of the supply of vaccines and associated items. As a result, elements such as tendering, costing, forecasting, production, and information exchange should be of high quality to ensure vaccines are always in stock (Chatterjee et al., 2016; IFPMA, 2017; Portnoy et al., 2015). In the similar perspective, Shamsi et al. (2018) argues that ensuring timely and sufficient vaccine supply, especially during crises, requires a robust procurement process capable of handling unpredictable demand. They assert that supply contracts can serve as useful solutions to enhance procurement efforts and propose an option contract to improve vaccine availability. Their research highlights the crucial role of suppliers in effective distribution of relief items, while acknowledging that buyers must mitigate this supply uncertainty risk by contracting backup suppliers to create a resilient supply chain in the event of a crisis. While our solutions are consistent with Shamsi et al. (2018) findings, both of our findings implications varies in several important ways. While Shamsi et al. (2018) stress the necessity of strong procurement processes and supply contracts, particularly option contracts, to deal with uncertain demand and assure timely vaccination delivery, our analysis examines the entire VSC of child immunization

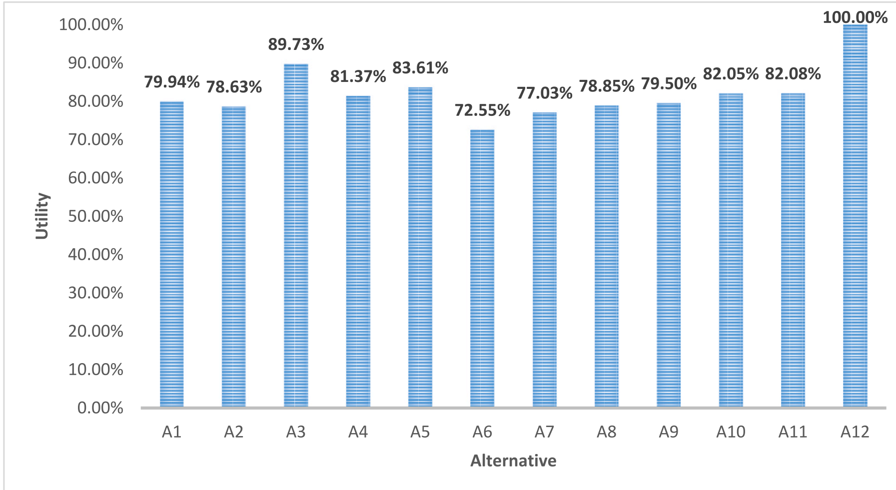

Fig. 5. Utility score of twelve alternatives.

rather than just supply and demand concerns. Our framework provides a structured approach that enables decision-makers to address the most crucial aspects influencing VSC in India Furthermore, our results emphasizes enhanced monitoring systems and demand forecasting as key solutions, whereas Shamsi et al. (2018) results focus on procurement methods and suppliers' roles in successful distribution.

UIP policymakers could implement the third potential solution, which involves establishing an authorized body to handle shortage issues. Masemola et al. (2025) indicate that in low- and middle-income countries such as South Africa, public trust in authorities was significantly undermined during the COVID-19 pandemic due to corruption scandals and frequently misguided prohibitions, which reinforced neoliberal arguments while exacerbating poverty, social exclusion, and the marginalization of the nation's most impoverished populations. Consequently, it is imperative for UIP to create an authorized body and at the same time upholds transparency and public confidence in its activities related to vaccine shortages. This would enable the acquisition of crucial information pertaining to shortages from a single official source, as opposed to collecting it from multiple levels within immunization programs. This approach can facilitate the implementation of improved strategies to address shortages and prevent disruptions in immunization program operations due to vaccine unavailability. More importantly, given the current surge in infectious diseases, it is crucial for those responsible for immunization programs to prioritize the issue of vaccine shortages and develop strategies to guarantee that no child is deprived of access to vaccines at health facilities due to a stockout.

6.1. Theoretical implications

Vaccine shortages primarily impact vaccination rates and have a lasting effect on the overall operation of the VSC. The introduction of novel vaccines to mitigate the increasing prevalence of diseases, coupled with several uncertainties, exacerbates the challenges faced by vaccination programs in the event of shortages. This research specifically examines potential solutions that might assist the Government of India (GoI) immunization division and policymakers in effectively managing VSC issues during periods of scarcity. The study employs an integrated framework that combines the AHP and COPRAS-G methodologies and provides some novel insights to policymakers. We show that, similar to the supply chain of other perishable goods (Aljuneidi, Punia, Jebali, & Nikolopoulos, 2024; Kumar, Kumar, Saini, & Pratap, 2022), the unpredictability of demand is a substantial barrier to reducing shortages and improving the performance of the VSC. Several factors contribute to demand uncertainty in India, such as inadequate infrastructure, significant travel distances to vaccination facilities, insufficient information exchange, and a shortage of staff (Chandra & Kumar, 2018; S. Kumar et al., 2023; A. K.Yadav et al., 2023; Sinha et al., 2023). These challenges make it difficult for immunization decision-makers to estimate the future demand. Insufficient assessment of demand frequently leads to vaccination shortages. Expanding the storage capacity beyond the current one-month limit for lower-tier supply chains or outsourcing the capacity to a third party may be a viable alternative. However, owing to budgetary limitations, adopting these solutions may not be feasible for GoI. We suggest that the vaccination division may find a viable answer in a more cost-effective monitoring system to quantify shortages. Immunization programs should regularly evaluate vaccine inventories and promptly inform the relevant authorities if they anticipate a shortage at any point in the supply chain or in the future due to an unexpected surge in demand, poor supply, or any other relevant factor. Additionally, fostering an integrated work culture that promotes seamless data exchange among all stakeholders would also be beneficial. Moreover, it will enhance information and coordination among VSC partners, resulting in better decisions on production capacity planning, which is a significant factor causing VSC shortages, as indicated in our study.

We show that regulatory complications are a significant contributing factor to shortages in VSC. Because of the strict regulatory restrictions, the process of registering a vaccine is intricate and requires a significant amount of time. A vaccine undergoes a pre-clinical evaluation and three cycles of clinical trials before receiving approval for the Indian market. Building state of the art manufacturing facilities is essential to getting a license from the WHO (Gupta et al., 2013; Salalli et al., 2023). To reduce rejection rates and ensure timely manufacturing and delivery of vaccines, it is critical to have a clearly defined plan for regulatory issues that will facilitate the efficient functioning of vaccination programs. Our analysis reveals that inadequate coordination in the supply chain can lead to shortages in VSC. While healthcare institutions in developed countries have seen significant benefits in coordinating their supply chains through effective supply contracts (Chick et al., 2017; Joshi et al., 2023), decision-makers in low- and middle-income countries continue to face challenges in this area (Chandra & Vipin, 2021). Efficiently overseeing the operations of vaccination programs is possible by effectively managing shortage risk during supply and demand uncertainty through VSC coordination.

Our findings indicate a relationship between vaccine shortages and the frequent adjustments made to immunization program schedules. Due to the scarcity of child immunization vaccine suppliers worldwide and the challenges they face in meeting high demand and supply uncertainty, any alterations to the immunization schedule can pose difficulties in fulfilling orders within a shorter timeframe (Chebolu-Subramanian & Sundarraj, 2021). Therefore, we recommend that policymakers minimize alterations to the immunization schedule. In the end, we demonstrate that vaccine waste results in shortages. Every year, millions of vaccine doses are wasted globally (Jacobson et al., 2004; Mvundura et al., 2023). This waste occurs due to a variety of reasons, including transportation issues, expiration dates, open or closed vials, temperature inconsistencies, and quality concerns. These issues can result in shortages during times of increased demand, which can place a significant financial and labor burden on the government and healthcare workers. In conclusion, our framework offers valuable theoretical insights for effectively addressing shortages in VSC. To address VSC shortages, it is essential to effectively manage production, coordination, demand uncertainty, and information sharing issues.

6.2. Operational implications

Chandra & Kumar (2020) study reveals that operational and financial issues are the main factors contributing to the delay in vaccine delivery. Furthermore, demand forecasting, communication between supply chain members, and planning and scheduling are critical issues in the VSC of India. These three critical issues affect every other element of the VSC, including vaccine shortages, either directly or indirectly. Our research reveals that the decision-makers can mitigate the adverse effects of these issues on the shortage problem in immunization programs by improving the purchasing process, enhancing the accuracy of forecasting systems, enhancing the monitoring systems' ability to identify shortages, and establishing technology infrastructure at various supply chain levels for buffer stocks.

An improved forecasting system has the potential to reduce forecasting errors and, when combined with effective supply control, can facilitate supply alignment with actual demand. In the end, taking this action might potentially decrease the government's operating expenses related to shortages, waste, reordering, storage, transportation, and administration. Yadav et al. (2023) highlights that blockchain technology, when integrated with IoT, can greatly enhance trust, transparency, traceability, and data management within the VSC. Today's healthcare organizations require real-time information sharing in their supply chain to accurately capture supply and demand status. However, developing countries such as India lack the necessary technological infrastructure to implement and maintain advanced forecasting and information systems, particularly in rural regions. The scarcity of well-educated supply chain managers and low digital penetration are the main obstacles. The geographical inequalities in rural India indicate that regions in close proximity to metropolitan centers have a greater propensity for embracing digital skills owing to superior infrastructure and educational accessibility. On the other hand, distant rural regions face difficulties such as limited connection, which leads to lower adoption rates and poor information sharing on immunization schedules (Sindakis & Showkat, 2024; A. K. Yadav et al., 2023). To address these inequalities, it is necessary for GoI to enhance the infrastructure, implement digital literacy initiatives, and raise awareness about immunization in rural areas. Our findings are consistent with those of Yadav et al. (2023) where both studies aim to enhance the VSC in India. The most prominent solutions as also highlighted by Yadav et al. (2023) in VSC India is the need for changes in organizational structure and policies, which poses significant resistance to adopting new technologies. Additionally, the requirement for large-scale IoT infrastructure and the lack of technical expertise are found to be the most impactful solutions to improve overall VSC efficiency.

Our findings suggest that various factors, including the monitoring and reporting of shortages, the collaboration of supply chain experts, stakeholders, government organizations, healthcare professionals, and pharmacists, and the transparency of industry notifications of shortages, could potentially assist immunization divisions in managing planning and scheduling issues effectively. Insufficient or incorrect information throughout the planning process can lead to irrational decisions in VSC, which can cause consumer dissatisfaction and place extra strain on the government, society, and the environment. An effective governing authority that communicates the projected or current extent of shortages to all participants in the supply chain may undoubtedly assist decision-makers in formulating improved operational strategies for the future. This necessitates the participation of all key stakeholders in the decision-making process to reach a mutually beneficial consensus for all parties involved. Furthermore, the solutions provided in our integrated framework can be beneficial in managing shortages caused by operational issues such as vaccine cold chain monitoring, transportation disruptions, inventory management, and lead time.

6.3. Managerial implications

In today's environment, it is of utmost importance for immunization programs to enhance vaccine accessibility by reducing instances of insufficient stock at healthcare facilities. In addition, policymakers must undertake the task of identifying the root causes of vaccine shortages within the supply chain and implementing appropriate policies or remedies to mitigate these challenges. To help policymakers with better planning and preventative actions, it is crucial for VSC managers to possess a comprehensive understanding of the underlying factors contributing to vaccine shortages throughout every stage of the supply chain. To assist policymakers in formulating appropriate strategies that consider the unique attributes of vaccination programs in India, we directed our focus towards identifying key factors contributing to vaccine shortages. The development of a MCDM, coupled with a priority assessment and ranking of the causes and solutions, is also a significant outcome. In India, supply chain managers possess considerable proficiency in managing vaccination programs. However, they demonstrate a deficiency in skills for improving decision-making by utilizing contemporary qualitative and quantitative models. Therefore, this study's proposed framework holds significant potential for VSC managers seeking to optimize their time and financial resources to address the primary causes of vaccine shortages. In light of the COVID-19 pandemic and other future outbreaks, it is interesting to point out that the implementation of a better monitoring system to measure shortages represents a highly effective strategy for managers. In this respect, the utilization of a centralized information channel to provide timely and accurate data on supply, consumption, demand, and shipment could potentially have a significant impact on UIP India. Such information sharing strategies to improve supply chain visibility can provide an exceptional capacity for managers to overcome shortages observed throughout the supply chain. The government can start helping VSC managers improve information exchange through innovative technologies like radio frequency identification and artificial intelligence.

7. Conclusion, limitations, and future scope

This paper identifies the causes of vaccine shortages in India's child immunization program, as well as potential solutions to address the shortage issues. We combined the AHP and COPRAS-G methodologies to create an integrated model that addresses 3 key research questions. The literature study, field survey in 3 states of India, and expert opinions yielded 10 causes of vaccine shortages and 12 solutions to address the shortages. The integrated model prioritizes causes and solutions, enabling decision-makers to concentrate on the most crucial aspects of the shortage issue. We demonstrate that uncertainty in demand is the primary cause of vaccine shortages, and a more effective monitoring system is the primary solution to overcome these shortages. Reducing the event of shortages is crucial for optimizing the efficacy of vaccination programs; therefore, policymakers should work on the aforementioned factors to reduce or eliminate the negative impact of vaccine shortages on the performance of child immunization programs. The process of validating solutions entails conducting a sensitivity analysis through Monte Carlo simulation, utilizing a uniform probability distribution within the interval [0, 1]. The simulation confirms the consistency of the results, identifying improved monitoring system to measure shortages (A12), a high-quality active procurement process (A3), and a collaborative approach by all stakeholders involved in the VSC (A5) as the top-ranked solutions. To our knowledge, no existing studies employ an MCDM framework to rank causes and solutions to manage vaccine shortages within child immunization programs in India or other developing countries. Our proposed framework, which directly addresses vaccine shortages, constitutes a significant contribution to the literature on the engineering management and offers key implications for policymakers and decision-makers. Moreover, given the current lack of robust strategies for quantifying and mitigating shortages in UIP India, our work provides valuable results for planning and implementing preventive and corrective measures, which can be useful not only to policymakers and decision-makers in India, but also to other developing countries with immunization programs that operate similarly to improve child immunization programs performance.

Although our study provides valuable insights for policymakers in UIP India and other countries dealing with shortages, it does have some limitations. One first limitation is that the data has been collected exclusively from specific states in India. As a result, there may have been a failure to consider certain causes and solutions that are applicable to other places within the country. The second limitation of the present study is the expert's reluctance to participate in the study and their hesitancy to answer certain questions owing to the nature of their government job. The third limitation of the study is the utilization of MCDM methodologies to prioritize causes and solutions. Due to the vulnerability of these approaches to the rank reversal problem, we have not thoroughly investigated this issue in this context. In general, we did not compare the result rankings using any other MCDM technique, and we solely used simulation to ensure the stability of the cause and solution rankings.

The future research can proceed as follows. To gain further insights into the shortage problem, it will be beneficial to collect samples from all states and union territories in India. Furthermore, the involvement of additional experts in the study can help to minimize biases in constructing the AHP and COPRAS-G final response sheets and enhance the credibility of the data analysis. We can further expand our work by incorporating the Pythagorean fuzzy concept into our integrated model. Finally, expanding the scope of our research in the future to include comparisons with alternative approaches may help us strengthen and validate our study findings.

CRediT authorship contribution statement

Dheeraj Chandra: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Shweta:** Methodology, Formal analysis, Data curation. **Amit Kumar Yadav:** Methodology, Formal analysis, Conceptualization. **Vipul Jain:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing 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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Appendix

Appendix A. . Description of methodologies

1. AHP

The Analytic Hierarchy Process (AHP) is a methodology for multi-criteria decision-making that was devised by L. Saaty with the aim of structuring and evaluating intricate decision-making problems (Saaty, 1977). In this method, the selected problem is transformed into a hierarchical structure comprising distinct levels, such as goal, criteria, and sub-criteria. Several supplementary methodologies, for instance, ANP, PROMETHEE, ELECTRE, and TOPSIS, have been proposed for addressing multi-criteria decision-making issues; however, AHP is recommended as a superior methodology compared to other approaches due to its broad applicability and ease of use (Luthra et al., 2016).

The various steps involved in the AHP methodology are discussed below:

Step 1: ***Define the problem.*** The first step is to identify the problem, which has to be solved using the AHP method.

Step 2: ***Construct the pairwise comparison matrix.*** Next step is to develop a pairwise comparison matrix between the criteria's with the help of the expert's opinions. Using Eq. A1-A2, the aggregated final judgment matrix of all k experts can be obtained.

$$a_{ij}^{*} = \sqrt[k]{a_{ij}^{*\,1} \times a_{ij}^{*\,2} \ldots\ldots a_{ij}^{*\,k}} \tag{A1}$$

$$A_{ij}^{*} = \left[a_{ij}^{*}\right] \tag{A2}$$

A_{ij}^{*} is an aggregated final judgment matrix, and a_{ij}^{*} is the assessments of factor i and factor j of k experts, i, j = 1,2,….,n. k is the number of experts.

Step 3: ***Check the consistency ratio.*** Calculate the consistency ratio of the pairwise comparison matrix with the help of the principal eigenvalue. The consistency ratio should be less than 0.1 according to Saaty in order to have consistency in the judgments of the decision-makers.

The consistency ratio for the matrix is calculated as follows:

$$C.R. = CI/RI \tag{A3}$$

Where, RI = random index and,

CI = consistency index.

The values of RI depend on the value of n (the number of factors/criteria or alternatives in the decision matrix).

In the calculation step of C.R., the Consistency Index (C.I.) is formulated as follows:

$$C.I = (\lambda_{\max} - n)/(n-1) \tag{A4}$$

$\lambda_{\max}$ is the Perron root or principal eigenvalue of the matrix $\tilde{A}$.

Step 4: ***Calculate the final weights.*** After the consistency is satisfied with a pairwise comparison matrix, a normalized AHP matrix is calculated by making the column sum of each factor of the aggregated final judgment matrix equal to 1. After obtaining a normalized AHP matrix, the final step is to compute the weights using Eq. A(5).

$$w_i = \frac{\left(\sum_{j=1}^{n} a_{ij}^{*}\right)}{n} \quad i = 1, 2, \ldots., n; \quad n = \textit{number of factors} \tag{A5}$$

2. COPRAS-G

According to Zavadskas et al. (2008), the Complex Proportional Assessment of Alternatives with Grey Relations (COPRAS-G) technique is a suitable approach for assessing various alternatives while considering multiple evaluation criteria. The utilization of grey theory applications involves a presentation of criteria values at intervals to obtain incomplete information in the judgments of decision-makers. The grey relational grade model has the potential to be highly efficacious in managing discrete data. The theory of grey systems employs the concept of a grey number as a fundamental tool for addressing uncertain information. This approach involves the use of white, black, and grey structures to model such information. In general, the white system is characterized by complete knowledge of internal information, while the black system is distinguished by the inability to obtain any information, characteristics, or properties. Thus, a grey system is defined as a system characterized by imprecise information lying between the white and black systems. The decision-making process, which involves dealing with incomplete information, can be facilitated by utilizing the grey system to classify numbers into white, black, and grey categories (Ecer, 2014; Nguyen et al., 2014; Zavadskas et al., 2008).

The various steps involved in COPRAS-G to calculate the utility degree and ranking of the alternatives are as follows:

Identify the most relevant criteria and alternatives to describe the problem.

Step 1: Construct a decision support matrix with the criteria value expressed in the intervals as follows:

$$X = \begin{bmatrix} [x_{11}, u_{11}] & [x_{12}, u_{12}] & \ldots. & [x_{1n}, u_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [x_{m1}, u_{m1}] & [x_{m2}, u_{m2}] & \ldots. & [x_{mn}, u_{mn}] \end{bmatrix} \quad i = 1, \ldots, m; j = 1, \ldots, n \tag{A6}$$

where m and n are the number of alternatives and criteria's respectively and $[x_{ij}, u_{ij}]$ is the interval value of the i_{th} alternative with respect to the j_{th} criteria. Further, x_{ij} is the lowest value or the lower limit and u_{ij} is the highest value or the lower limit.

Step 2: Normalize the data of the decision support matrix X using Eqs. A7-A9.

$$[\overline{x}_{ij}]_{m\times n} = \frac{2x_{ij}}{\left[\sum_{i=1}^{m} x_{ij} + \sum_{i=1}^{m} u_{ij}\right]} \tag{A7}$$

$$[\overline{u}_{ij}]_{m\times n} = \frac{2u_{ij}}{\left[\sum_{i=1}^{m} x_{ij} + \sum_{i=1}^{m} u_{ij}\right]} \tag{A8}$$

Therefore, a normalized decision support matrix will be written as follows:

$$\overline{X} = \begin{bmatrix} [\overline{x}_{11}, \overline{u}_{11}] & [\overline{x}_{12}, \overline{u}_{12}] & \ldots. & [\overline{x}_{1n}, \overline{u}_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [\overline{x}_{m1}, \overline{u}_{m1}] & [\overline{x}_{m2}, \overline{u}_{m2}] & \ldots. & [\overline{x}_{mn}, \overline{u}_{mn}] \end{bmatrix} \tag{A9}$$

Step 3: Construct a weighted normalized decision support matrix $\widehat{x}$ by using Eqs. A10-A12.

$$\widehat{x}_{ij} = \overline{x}_{ij} \times q_j \tag{A10}$$

$$\widehat{u}_{ij} = \overline{u}_{ij} \times q_j \tag{A11}$$

where i = 1,2,.,m; j = 1,2,…,n and q_j is the weight of the j_{th} criteria.

The results of the weighted normalized decision matrix are written as follows:

$$\widehat{X} = \begin{bmatrix} [\widehat{x}_{11}, \widehat{u}_{11}] & [\widehat{x}_{12}, \widehat{u}_{12}] & \ldots. & [\widehat{x}_{1n}, \widehat{u}_{1n}] \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ [\widehat{x}_{m1}, \widehat{u}_{m1}] & [\widehat{x}_{m2}, \widehat{u}_{m2}] & \ldots. & [\widehat{x}_{mn}, \widehat{u}_{mn}] \end{bmatrix} \tag{A12}$$

Step 4: Calculate the weighted mean normalized sums P_i of those criteria whose larger values are more desirable (optimization path of maximization type) and weighted mean normalized sums R_i of those criteria which whose smaller values are more desirable (optimization path of maximization type).

$$P_i = \frac{1}{2}\sum_{j=1}^{k}\left(\widehat{x}_{ij} + \widehat{u}_{ij}\right) \tag{A13}$$

$$R_i = \frac{1}{2}\sum_{j=k+1}^{m-k}\left(\widehat{x}_{ij} + \widehat{u}_{ij}\right) \tag{A14}$$

k is the number of maximization type criteria's and (m-k) is the number of minimization type criteria's.

Step 5: Calculate the minimum value of R_i:

$$R_{\min} = \min R_i \; (i = 1, 2, ..., m) \tag{A15}$$

Calculate the relative significance or weights of each alternative Q_i:

$$Q_i = P_i + \frac{R_{\min}\sum_{i=1}^{m} R_i}{R_i\sum_{i=1}^{m}\left({R_{\min}}/{R_i}\right)} = P_i + \frac{\sum_{i=1}^{m} R_i}{R_i\sum_{i=1}^{m}\left({1}/{R_i}\right)} \tag{A16}$$

Step 6: Determine the maximum weight of the alternative using Eqs. A17-A18.

$$Q_{\max} = \max Q_i \; (i = 1, 2, ..., m) \tag{A17}$$

Step 7: Calculate the utility degree of each alternative

$$U_i = \left(\frac{Q_i}{Q_{\max}}\right) \times 100\% \tag{A18}$$

Utility degree is obtained by comparing each alternative with the best alternative (the alternative having maximum weight). The value of utility degree ranges from 0% to 100%, where 100% indicates the best alternative. Rank the alternatives based on U_i values. The higher the value of utility degree the better is the alternative.

Data availability

Data will be made available on request.

The data that support the findings of this study are available upon reasonable request.

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